

CONDITIONING OF AIR BY DEHUMIDIFICATION WITH SORBENTS AND THEIR DESORPTION

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**by
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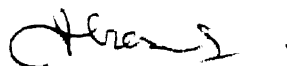
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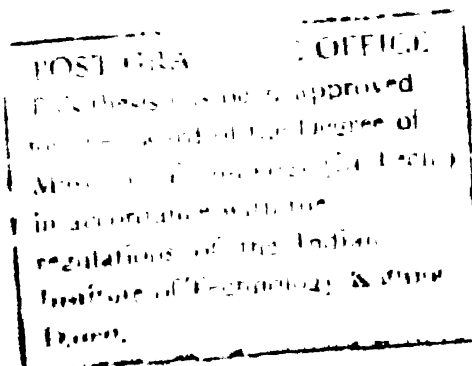
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NOMENCLATURE

c_p	Specific heat at constant pressure, J/kg-°K
COP	Coefficient of performance
DBT	Dry-bulb temperature
HE	Heat exchanger
m	Mass of air, kg
p	Pressure, N/m ²
t	Time, min
T	Temperature, °C
T_{db}	Dry-bulb temperature, °C
T_{DB}	Solar drier bed temperature, °C
T_{dp}	Dew point temperature, °C
T_e	Effective temperature, °C
T_w	Water Temperature, °C
T_{wb}	Wet-bulb temperature, °C
w	Humidity ratio, kg _w /kg _a
WBT	Wet-bulb temperature
x	Moisture content, kg _w /kg _A
ϵ	Heat exchanger effectiveness
η_H	Humidifier efficiency, %
ϕ	Relative humidity, %

Subscripts

A	Refers to adsorbent
a	Refers to air
c	Refers to cold condition
e	Refers to exit condition
h	Refers to hot condition
i	Refers to inlet condition
W	Refers to water

SYNOPSIS

The present problem is an attempt towards development of an air conditioning system for hot and high humid environment requiring less electrical energy and utilizing unconventional energy resources. The principle involves dehumidification of air followed by its sensible and finally evaporative cooling to get the desirable state of conditioned air. It has been observed that the silica-gel bed either in adiabatic^{or} in cooled condition renders the rate of dehumidification much larger than the copper sulphate bed. On the other hand calcium chloride becomes liquid during the process of dehumidification. Its regeneration is not possible even with a high quality flat plate collector providing an operating temperature on the order of 120°C. It has also been found that copper sulphate takes the powdered form in 2 to 3 cycles of dehumidification and regeneration, causing excessive flow resistance by blocking the voids. The states of adsorption and regeneration of silicagel can be visualized more clearly by distinct change in colour of silicagel as compared to copper sulphate.

The dehumidification of air by sorbents has been accomplished under simulated inlet air conditions usually prevalent in high humid seasons in tropical countries like ours.

Five types of systems starting from simple to quite intricate one, have been theoretically analysed for the same operating variables. System III has been found to render reasonably **good** performance.

CHAPTER-1

INTRODUCTION

1.1 DESCRIPTION

The increasing cost of electrical energy, depleting nature of conventional source of energy and exorbitant cost of vapour-compression air conditioning systems have led to considerable diversification in the search of alternate methods for the maintenance of desired environmental condition. The evaporative cooling for human comfort and commercial applications [1] is one of the methods in such ^{an} endeavour. The use of such system, though not a substitute for usual air conditioners, has become the matter of public preference for maintaining reasonably comfort condition in residential buildings, offices, shops, business centres, theatres, warehouses etc.

Though the ASHRAE chart [2] exhibits 21°C as the effective temperature for human comfort for summer condition, the involvement of cost factor elevates the effective temperature to a value of about 26°C [3], causing considerable saving in energy and simplification in the system design.

Moreover, for the tropical countries like India, the effective temperature may be kept even higher in order to reduce the energy requirement by using evaporative cooling systems (such as a desert cooler). Such system is not only much cheaper than the conventional air conditioner but takes less electrical energy as well, in addition to less heat shock to human body [4].

Though the evaporative cooling is on one hand advantageous and is gaining public preferences over the existing systems, ~~but~~ its performance proves to be quite ineffective in presence of high relative humidity in the environment. Therefore, it is not suitable for coastal areas and in rainy season. For such situations, it has been reported by many researchers in the recent past that the removal of moisture from air using sorbents followed by sensible and evaporative cooling of the air has ~~shown~~ a promising prospect in the area of air conditioning. The use of adsorbents for moisture removal has become economically an attractive alternative in view of increasing energy cost and accompanying pressure for energy conservation [5].

1.2 REVIEW OF PREVIOUS WORK

Many researchers are working in the area of sorbent dehumidification. Work done by some of them is being briefly mentioned here.

Threlkeld [6] has presented the simple thermodynamic aspects of sorbents acting as dehumidifying agents and put forth the governing equations for the isothermal and adiabatic adsorbent beds in addition to liquid dehumidifying system. The solutions of these equations are quite complicated due to involvement of material properties and system variables.

The possibility of the use of desiccants in the cooling systems has been studied by Olsen [7] to improve their performance. He has compared the solid and liquid desiccant cooling systems with the absorption refrigeration system. Special attention was given to the direct use of solar energy for concentrating or drying the desiccants. But, the increased power requirement for pumps and fans or blowers has been felt due to lower regeneration temperature. Therefore, a combined system that uses desiccants to remove moisture and absorption refrigeration to do the cooling, has been suggested.

A thin adiabatic desiccant bed was designed and tested by Clark, et al [8] for solar air conditioning applications. But, they have found appreciable discrepancies between theoretical and experimental values.

The paper of Coellner [9] deals with the reduction in energy by means of a sorption dehumidifier being reactivated by inexpensive energy, such as solar hot water,

waste steam, or recovered process exhaust heat. It examines energy-efficiency (based on low grade energy for regeneration and electrical energy for circulation of air) as a function of the degree of dryness produced in an air stream.

A complete theoretical study has been done by Hougen and Marshall [10] for isothermal conditions using a linear equilibrium relationship between the adsorbate content of the gas and of the solid.

The equilibrium relations and governing equations of the sorbents are usually of non-linear type. Their solutions are generally found by numerical technique which involves large computing time. Linearized governing equations have been developed by Mathiprakashan and Lavan [11] for adiabatic fixed bed and rotating type dehumidifiers. The results of linear and non-linear solutions reveal a good agreement for a broad range of operating conditions in addition to significant saving in computing time for the linear model.

Peng and Howell [12] have analysed the hybrid double absorption cooling systems for low grade thermal energy applications. They have selected lithium-chloride water solution working on low grade thermal energy between 55-80°C. The thermodynamic studies of these systems have shown that they have definite advantages over conventional absorption and desiccant systems.

Close and Dunkle [13] have suggested the use of sorbent materials as energy storage and dehumidification cooling systems. They have found that these materials could reduce the store volumes compared to water or gravel energy stores for long periods of time without significant losses. They have found that the cost of the system could be reduced by combining the energy store and dehumidifier.

An overview of solar cooling systems was presented by Shelpuk [14] using adsorption and desorption processes. An advanced desiccant cooling system rendered COP in the range of 0.6 - 0.8 having solar collector output temperature on the order of 70°C. The desiccant cooling system integrated with a collector system has got good potential for achieving a higher cooling capacity per unit of solar energy input than alternate solar cooling techniques.

Several combined air based solar heating and solar desiccant cooling systems have been analysed on a digital computer for silicagel desiccant model by Oonk et al [15]. Four desiccant cooling cycles were analysed for New York city. These cycles included one which provided the house 100% ventilation air, and three cycles involving recirculation of the house air with various outside air flow configurations for regeneration. Results from these simulations indicated that the simple recirculation cycle gave the best overall system performance for the New York site.

1.3 THE PRESENT WORK

It involves the fabrication and installation of the set-up comprising sampling and dehumidification sections to provide broader flexibility to facilitate the experimental study at desired conditions. The dehumidification of moist air has been achieved by passing it through the adsorbent (silicagel) and absorbent (copper sulphate and calcium chloride) beds. The tray type and cylindrical beds have been used for dehumidification and the flat plate solar drier for their regeneration. The results for various cases have been compared to get the best choice.

Out of three sorbents studied, the silicagel has been found to be best suited for dehumidification of air. Its regeneration was also quite efficient in flat plate solar drier. The distinct changes in colour during dehumidification and desorption processes, provide an easy guide line for changing the processes.

A comparative analysis has been carried out for five systems in order to select the best one. It is found that the system-III (Fig. 2.4) ~~is found~~ offers the best choice. However, it has been felt that cooling of the adsorbent bed should be done by the air used in regenerative heat exchanger in system-III.

CHAPTER-2

COOLING AND DEHUMIDIFICATION PROCESSES

2.1 EVAPORATIVE COOLING

The cooling and dehumidifying of space is a form of air conditioning that has been recognized recently as an important simple device for comfort cooling. Even though, the cooling efficiency is not comparable to that of an air conditioning system, it does provide comfort conditions quite conducive to efficient working of human beings under hot and dry weather conditions.

Among many cooling processes the evaporative cooling is most commonly used for various applications where the relative humidity or the dry-bulb temperature is to be controlled. When water comes in direct contact with the ambient air, cooling of water and/or air takes place depending upon the combined effect of the following processes which differ physically from each other [16,17]:

- (a) surface evaporation of water and transfer of latent heat of vaporization from water
- (b) sensible heat transfer by conduction and convection
- (c) heat transfer by radiation.

Heat transfer by radiation is important only in the case of open large areas. In other cooling devices, however, this effect is generally insignificant and ignored. Between the remaining two heat transfer processes, the process of surface evaporation predominates. Hence, the cooling of water and/or air by evaporation is always termed as "evaporative cooling". However, this is controlled by the amount of moisture present in the air.

2.1.1 Limit of Direct Evaporative Cooling

The upper limit of sensible cooling achieved by evaporative method is limited by the saturation state of air leaving the humidifier. However, this state of air may be comfortable only if the effective temperature (T_e) for the leaving air is below 20°C [2]. In case of higher T_e ($> 20^\circ\text{C}$) the relative humidity of air beyond 75% is hardly recommended for comfort air conditioning, of course, the same is further affected by the higher value of T_e . It implies, therefore, that the evaporative cooling is not effective in hot humid coastal regions and other areas during the monsoon season. Under such situations, the utilization of evaporative cooling technique will call for dehumidification and sensible cooling before humidification of the air. By this method, a lower temperature having humidity within the tolerable limit may be achieved. It

means that the method of dehumidification will be a controlling factor for exploitation of this technique.

2.2 DEHUMIDIFICATION

Dehumidification is the reduction of the water-vapour content of air. The term, thus, describes a special case of dehydration which covers the removal of moisture in any form from a gas. The degree of dehumidification required varies greatly with different applications, and is one of the prime considerations influencing the choice of a method.

Within the past decade, drying of gases has become an increasingly important operation. Some of the more important commercial applications include the following:

- (1) Independent humidity control in air-conditioned spaces-comfort air-conditioning generally requires the maintenance of summer temperature between 24 to 26°C and relative humidity between 45 to 55%. The maintenance of these conditions with refrigeration system is quite expensive. There are numerous cases (e.g., assembly halls, restaurants, night clubs, fallout shelters, large buildings or hotels located in high humidity areas) in which the latent heat load is larger than the sensible heat load, where the use of

sorption system in conjunction with refrigeration system will give optimum results.

- (ii) Lowering of the relative humidity to facilitate handling of hygroscopic materials.
- (iii) Drying air for wind tunnels.
- (iv) Dehydrating natural gases.
- (v) Providing protective atmospheres for the heat treatment of metals.
- (vi) Maintaining controlled humidity condition in warehouses for storage.
- (vii) Drying of gases which are to be liquefied
- (viii) Manufacturing of drugs and chemicals.
- (ix) Candy, chocolate and chewing gum manufacturing.
- (x) Assembly of motors and transformers.
- (xi) Manufacturing of electronic components such as transistors and micro-wave components.

2.2.1 Methods of Dehumidification and Their Limitations

There are several ways to dehumidify the moist air. Some of the commonly used methods are described here in detail.

1. CHILLING

In this process, we cool the air below its dew point with the help of cooling coils to remove the moisture content. It can be explained by Fig. 2-1(a). State-1 shows the inlet air condition and state-2 is the desired condition. The air is first cooled to a temperature T_2 , by cooling coils, which is less than its dew point temperature, T_{dp} . Points-2' and -2 are having the same moisture level. The air at state-2' is then heated to reach the final state-2.

This process, though quite effective, involves unnecessary cooling and heating. This wastage of energy is generally overcome with the help of well known by-pass method shown in Fig. 2.1(b). In this method, only part of the ambient air is cooled by cooling coils upto the temperature T_3 ($< T_{dp}$) and then mixed with the ambient air in a proportion such that the desired state-2 is achieved.

The by-pass method, however, cannot be used always because of the following constraints:

- (a) The line joining the inlet state-1 and the desired state-2, should meet the saturation curve.
- (b) The temperature T_3 as shown in Fig. 2.1(b) should not be less than the freezing temperature of water.

2. COMPRESSION

Where an air-water vapour mixture is compressed, its ability to hold water is decreased, and simultaneously the water vapour starts condensing at a higher temperature, and the dew point of the mixture at elevated pressure becomes higher than that of the same mixture at atmospheric pressure. This process can be explained with the help of Fig. 2.1(c).

Ambient air has been shown by state-1 having humidity ratio w_1 . Its dew point temperature at atmospheric pressure is T_{dp_1} . For pressure p_1 ($p_1 > p_{atm}$) its dew point temperature becomes T_{dp_1} . At this pressure, the humidity ratio is not reduced. If the air is compressed further, the water vapour starts condensing. At pressure p_2 ($> p_1$), the dew point rises upto T_{dp_2} and the humidity ratio is reduced to w_2 . The final state is shown by point-2.

It is, however, a costly process because of the use of a compressor. The system could become economical where high pressure air is required.

3. EVAPORATIVE COOLING WITH CHILLED WATER

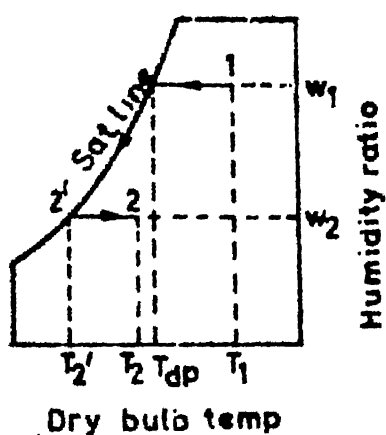
If the chilled water, having temperature less than the dew point of air, is sprayed in an evaporative

cooling system, the outgoing air will be cooled and dehumidified.

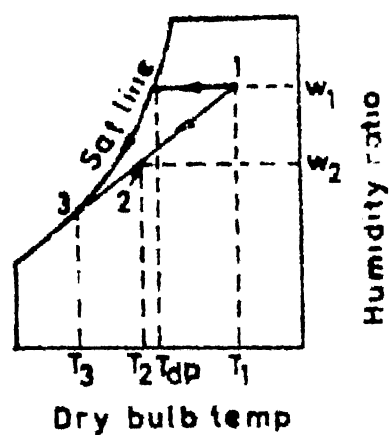
If the inlet air condition is at state-1, the desired condition-2 of the air can be achieved by spraying water at a temperature T_w ($< T_{dp}$), Fig. 2.1(d). The drawback of the process is the requirement of chilled water, necessitating the use of some sort of refrigeration process. Also, the choice of the desired state of the exit air is restricted to points lying on the line joining the inlet state and the final state such that this line meets the saturation curve.

4. SORBENT MATERIALS

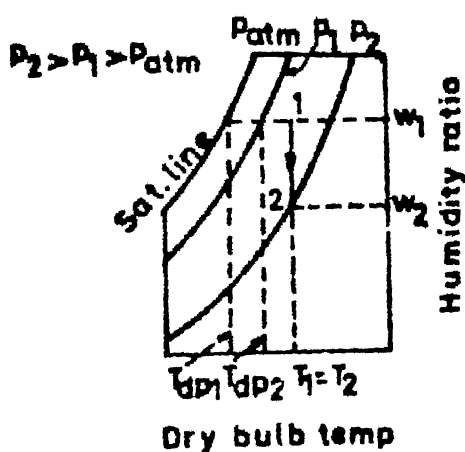
Sorbents are solid or liquid materials which have the property of extracting and holding other substances (usually gases or vapours, e.g., water vapour) brought into contact with them. The sorption process always generates heat, the major part of which is the result of the condensation of water vapour. The weight of water held by a substance will increase or decrease, depending upon whether the vapour pressure of the water held by the substance is less or greater, respectively, than the partial pressure of water vapour in the surrounding atmosphere. All materials are sorbents to a greater or lesser degree. However, the term sorbents refers to



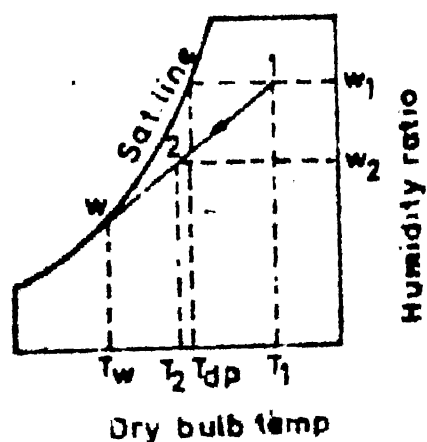
(a) Chilling method



(b) Bypass method



(c) Compression method



(d) Chilled-water spray method

FIG.2.1 DEHUMIDIFICATION BY VARIOUS METHOD

those materials having a large capacity for moisture as compared to their volume and weight. Such materials may be divided into two categories:

(i) Adsorbent

A sorbent which does not change physically or chemically during the sorption process is called ^{an} adsorbent. At no time is there a phase change of an adsorbent. Silica-gel, activated alumina, activated charcoal and activated boxite are some such materials.

Adsorption takes place at the surface of the adsorbent, where the air and solid come in contact with each other, i.e., at the interface. Materials that are used commercially as solid adsorbents have a porous structure of submicroscopic dimensions, which gives them an extensive internal surface area. This area may be as large as 1000 square meters per gram of adsorbent, and the internal pore radii only a few angstroms. In such materials capillary condensation is of great importance. It can occur only when the solid is wetted by the condensate, resulting in concave surfaces of the condensed liquid. The equilibrium vapour pressure of a liquid having a concave surface is less than the normal value by an amount depending on the radius of curvature. Thus, the amount of water-vapour adsorbed under equilibrium conditions is proportional to the surface area of the desiccant if the pores are large

enough to allow penetration of the adsorbate into the interior of the desiccant.

(ii) Absorbent

A sorbent which changes either physically, chemically, or both, during the sorption process is called absorbent. Calcium chloride, copper sulphate and magnesium sulphate are examples of solid absorbents and lithium chloride-water solution, lithium bromide-water solution, ethylene glycol and sulphuric acid are liquid absorbents.

Some materials absorb moisture in both the solid and liquid phases. Calcium chloride^{and} lithium chloride fall under this category. When water is absorbed by ~~the~~ calcium chloride, it is converted into a hydrate and reaches a saturation point at $\text{CaCl}_2 \cdot 2 \text{H}_2\text{O}$, after which additional moisture tends to cause the material to lose its crystalline shape and dissolve in the water that was absorbed. With additional water, there is a phase change from the solid into the liquid. It absorbs moisture in the liquid phase also depending upon the vapour pressure difference between the air and the solution.

Properties of Sorbent Materials

- (a) It should have suitable vapour pressure, i.e., less than the vapour pressure of ^{the} surrounding atmosphere.

- (b) Adsorptive capacity should be high.
- (c) Surface area should be high.
- (d) It should be, both chemically and physically stable within the range of operation. It should resist contamination from impurities.
- (e) It should be non-corrosive, non-toxic, odourless and inflammable.
- (f) It should be capable of regeneration/reactivation with methods and temperatures available.
- (g) It should be available in abundance at low cost.

Since our emphasis in the present work ~~has been~~ is on the use of solid adsorbents, a discussion on the adsorption systems is presented below.

2.2.2 Solid Adsorption Systems

When an active adsorbent comes into contact with a gas of high humidity, there is a tendency for the vapour pressure of the water in the adsorbent to reach ^{an} equilibrium with the partial pressure of the water in the surrounding gas, with the result that water is extracted from the gas by the adsorbent, and the moisture content of the gas is decreased. Dehumidification of the gas stream has thus occurred.

Dehumidification by a solid desiccant such as silicagel or activated alumina may be performed under either static or dynamic operation. In the static method, there is ^a natural circulation of the gas to be dried into, or through, the desiccant. The air immediately surrounding the adsorbent is initially dried and subsequently, through convection and diffusion, water vapour from spaces and objects farther away pass into the air surrounding the desiccant where it is adsorbed. Since considerable time may be required for the air and the desiccant to establish equilibrium, this type of dehumidification is best suited for small containers.

On the other hand, dynamic dehumidification is operated with forced flow of the air being treated through the desiccant bed. It requires a desiccant bed, a fan to force the humid air through this bed, and a heater or other means to periodically reactivate the adsorbent. As the air passes into the activated desiccant, it surrenders a certain amount of its water vapour. The rate of moisture pickup and the humidity condition of the leaving ^{air} are functions of ~~xxxxxx~~ many variables.

During the process of adsorption there is a liberation of heat which results in an elevation of the effluent air temperature. This heat is equivalent to the latent heat of vaporization of the adsorbed liquid plus an added quantity

known as the heat of wetting, which is defined as the heat developed when the liquid and the solid surface contact one another. The heat of wetting is relatively large when adsorbing the first water molecules on a freshly reactivated desiccant and tapers off to a very low value as the desiccant approaches saturation. As the adsorbed vapour condenses, the latent heat is converted into sensible heat. All of the released heat, known cumulatively as the heat of adsorption, is dissipated into the desiccant, the enclosure, and the passing air stream. In comfort air conditioning, it is often necessary to cool the effluent air prior to its introduction into the conditioned space, but in most other dehumidification applications, this heat is not objectionable, in which case no provisions are made for its removal. An operation of this type is called adiabatic process. However, in practice the heat generated in the adsorbent bed is removed by a cooling coil. Therefore, the actual process is neither isothermal nor adiabatic.

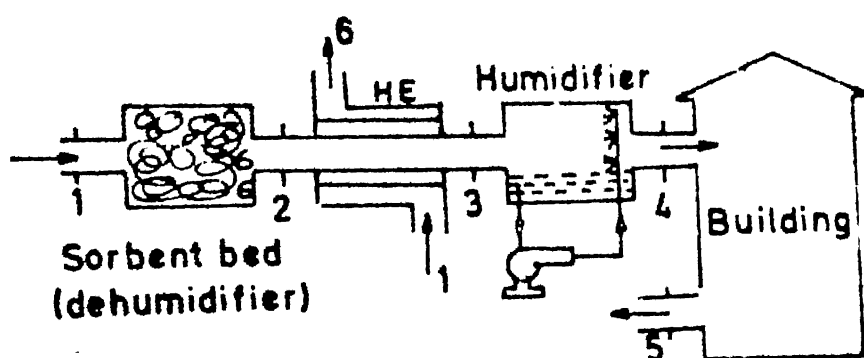
2.3 SOME PROPOSED SYSTEMS

The effectiveness of evaporative coolers depends strongly upon the dryness of air. However, locations near the sea coast as well as the regions of high rain fall are subjected to the moisture content in air ~~above~~ 75% relative

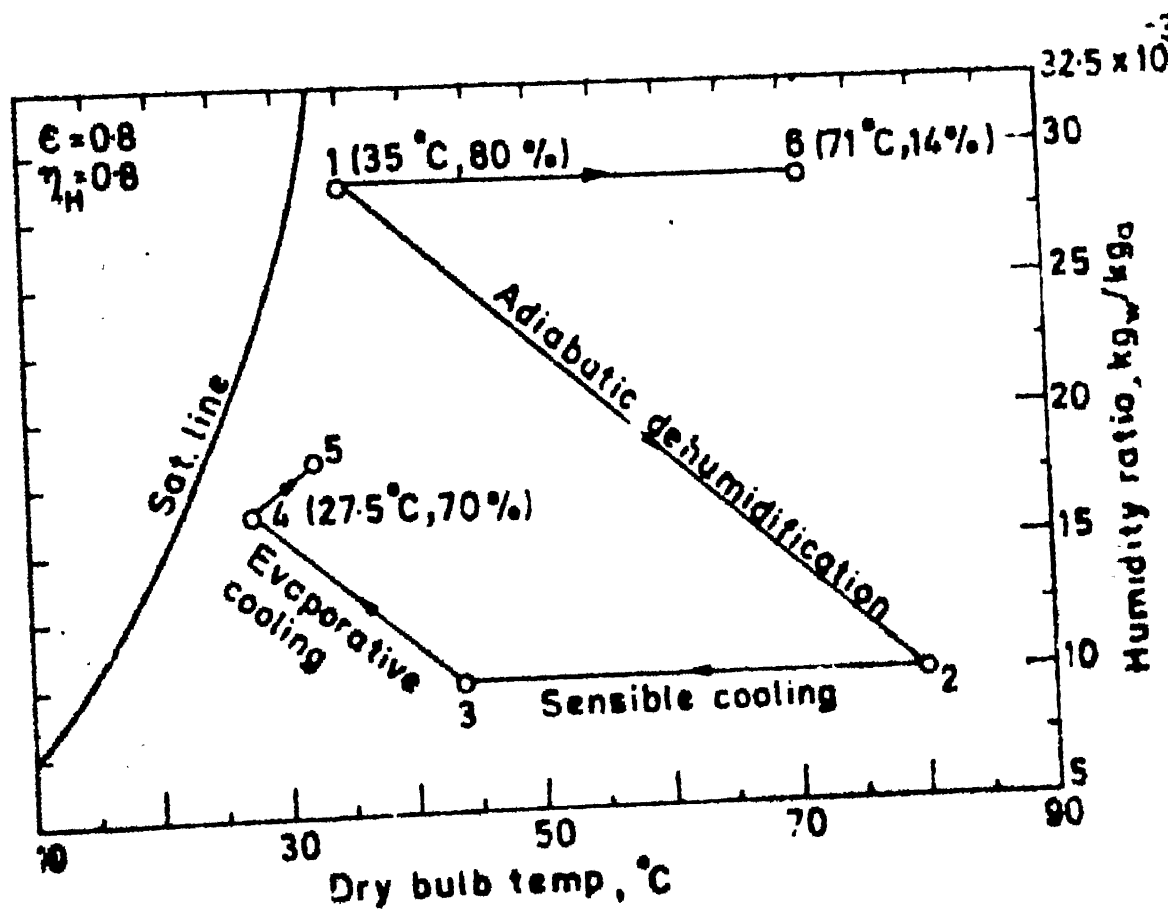
humidity. The natural evaporative cooling devices for human comfort become inefficient in such places. This problem can be solved to a great extent by dehumidifying the ambient air using a sorbent material followed by sensible cooling or evaporative cooling or a combination of both the cooling processes. There are many ways to design a dehumidification-cooling system. Five typical systems are analysed here for the same inlet-air-conditions in order to decide the most effective system. Thereafter, the latter system is analysed for different inlet air conditions, varying heat-exchanger effectiveness and humidifier efficiency. The description of various systems are as follows:

SYSTEM-I

The ambient air at a particular state-1 is passed through a sorbent bed followed by sensible cooling by means of a heat exchanger where the cooling medium is also the ambient air. The sensibly cooled air is further cooled by an evaporative cooling process by means of a humidifier and the air at the final state-4 is used for cooling of the required space. The air leaving the space may have the temperature and humidity lower than the ambient air. The system-arrangement and the various states of air drawn on a psychrometric chart are shown in Fig. 2.2.



(a) System arrangement



(b) The processes on psychrometric chart

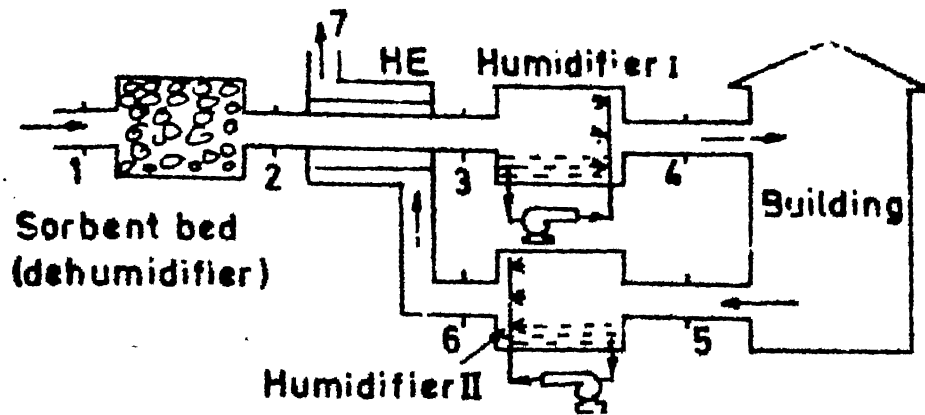
FIG.2.2 SYSTEM I.

SYSTEM-II

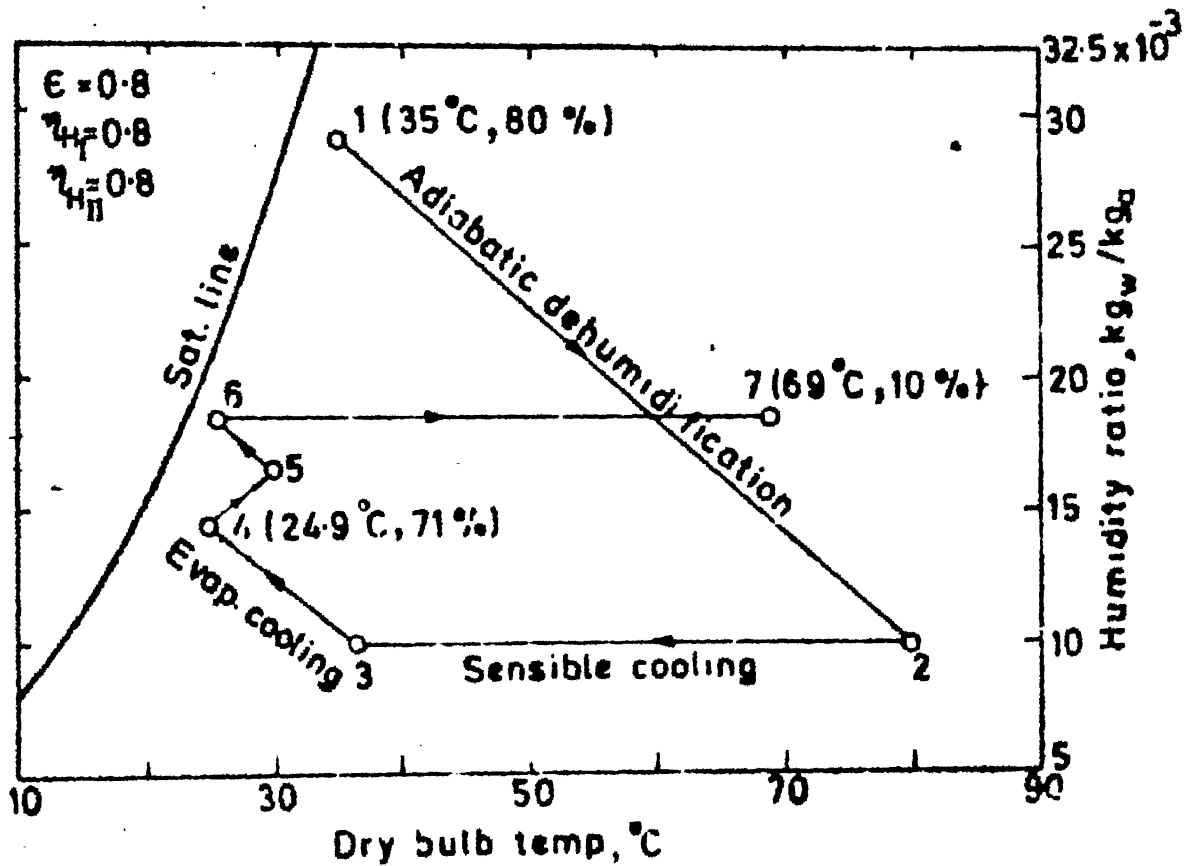
Since the temperature and humidity of air leaving the space in the above system are lower than the ambient air state, the former is further cooled by spray humidifier-II as shown in Fig. 2.3(a). This humidified air, after passing through the heat exchanger, cools the dehumidified air to a temperature lower than that of Case-I. The evaporative cooling of this air in the humidifier-I renders the air temperature and humidity lower than that achieved in Case-I. This cooled air is then supplied to the space being cooled. It, therefore, implies an improvement in the system shown in Fig. 2.2(a). The air leaving this space is again evaporatively cooled by the humidifier-II and used again as a cooling medium in the heat exchanger completing the cycle. The process continues till a steady-state is reached. The final state of the air and the system diagram are shown in Fig. 2.3. An iterative procedure is used to evaluate the final conditions of the air being achieved by various processes.

SYSTEM-III

A combination of the above two systems employs two heat exchangers for sensible cooling of the dehumidified air in addition to the two humidifiers-I and II. The dehumidified air is first cooled in the heat exchanger-I



(a) System arrangement



(b) The processes on psychrometric chart

FIG. 2.3 SYSTEM II.

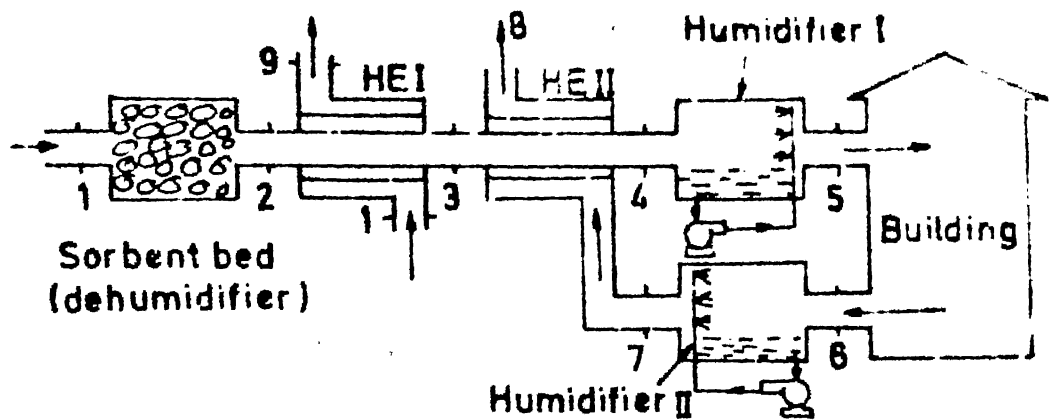
using ambient air, and further cooled in a regenerative heat exchanger-II using evaporatively cooled air leaving the space. The cooling process continues till it reaches a steady-state. The air attains a much lower temperature as compared to the previous two cases. The system and processes are shown in Fig. 2.4. The sample calculation for this system has been shown in Appendix-A.

SYSTEM-IV

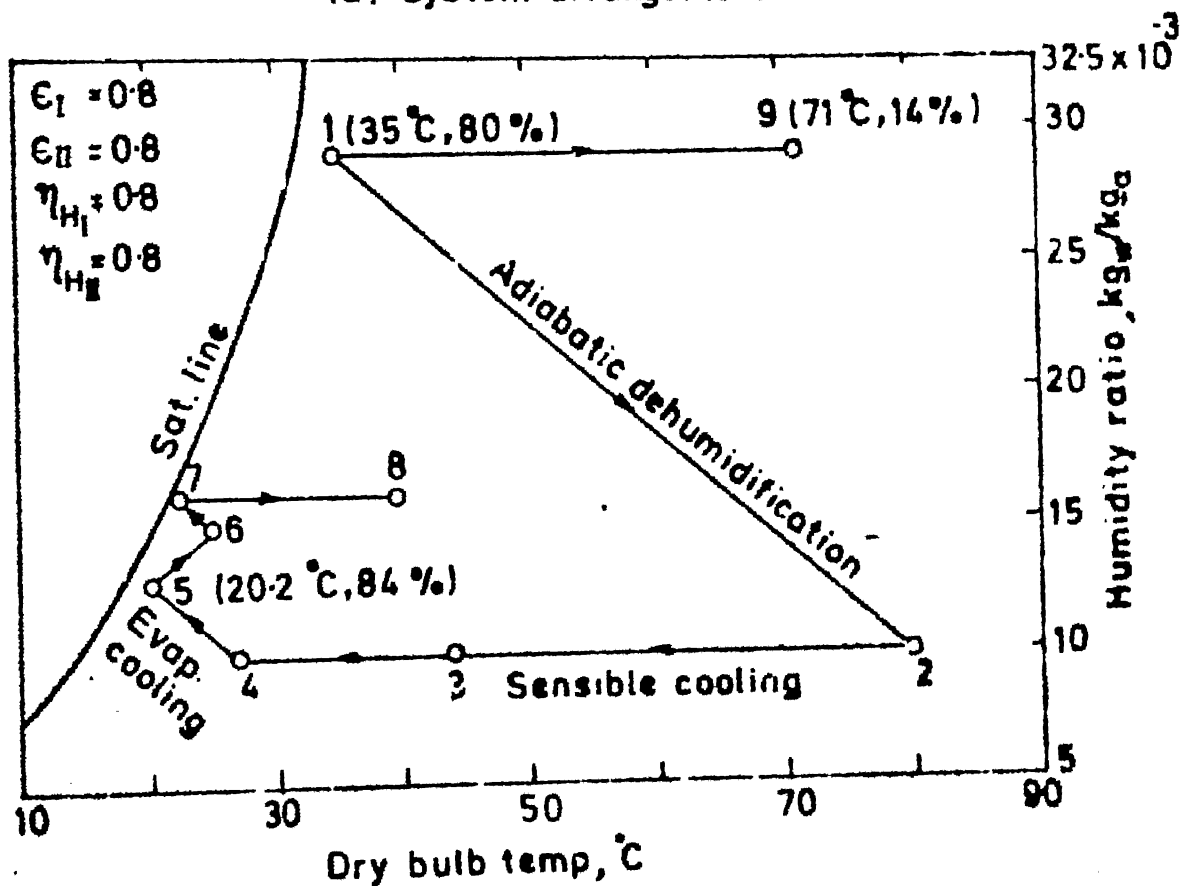
It incorporates a cooling coil in the adsorbent bed producing the dehumidified air. This air is passed through the humidifier-I and other components as described in the second case. The cooling process continues till it reaches the steady-state, as shown in Fig. 2.5.

SYSTEM-V

It is different from all the preceding systems in the sense that the room air is recirculated through out the process. It has, thus, ^{an} advantage over all other systems due to the fact that the low temperature return air augments the adsorption capacity of the bed. In this case the evaporatively cooled fresh air is used as a cooling medium in the heat exchanger. It is found that this system is better than the first two systems and inferior to systems III and IV. Figure 2.6 shows the schematic diagrams of the system and the psychrometric processes.

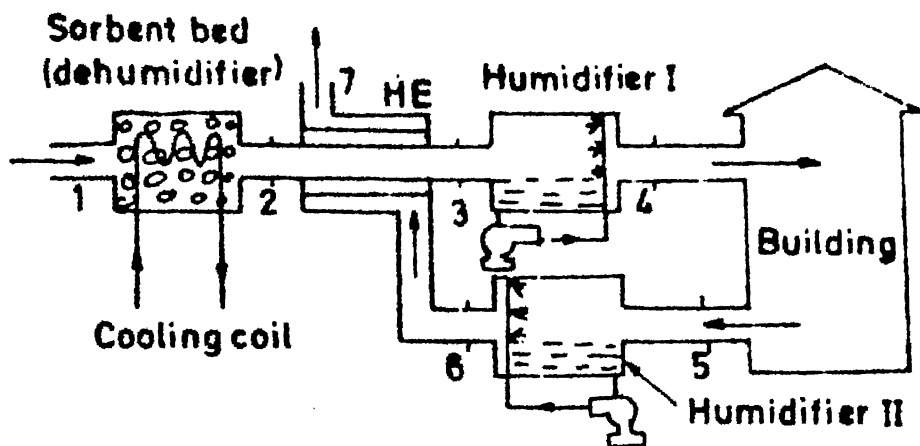


(a) System arrangement

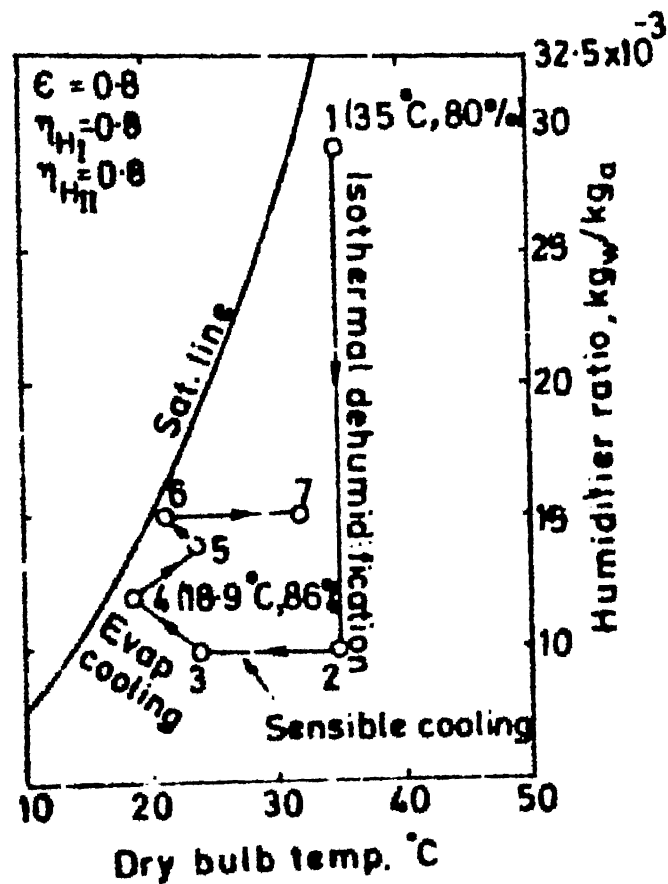


(b) The processes on psychrometric chart

FIG. 2.4 SYSTEM III.

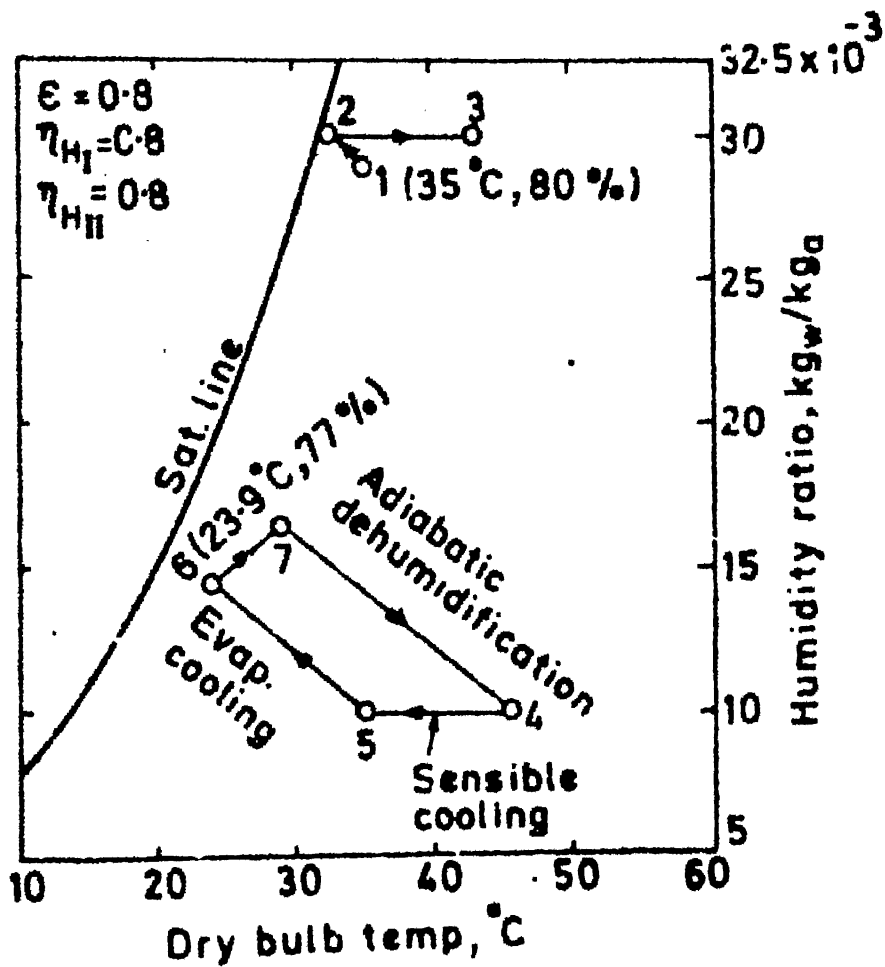
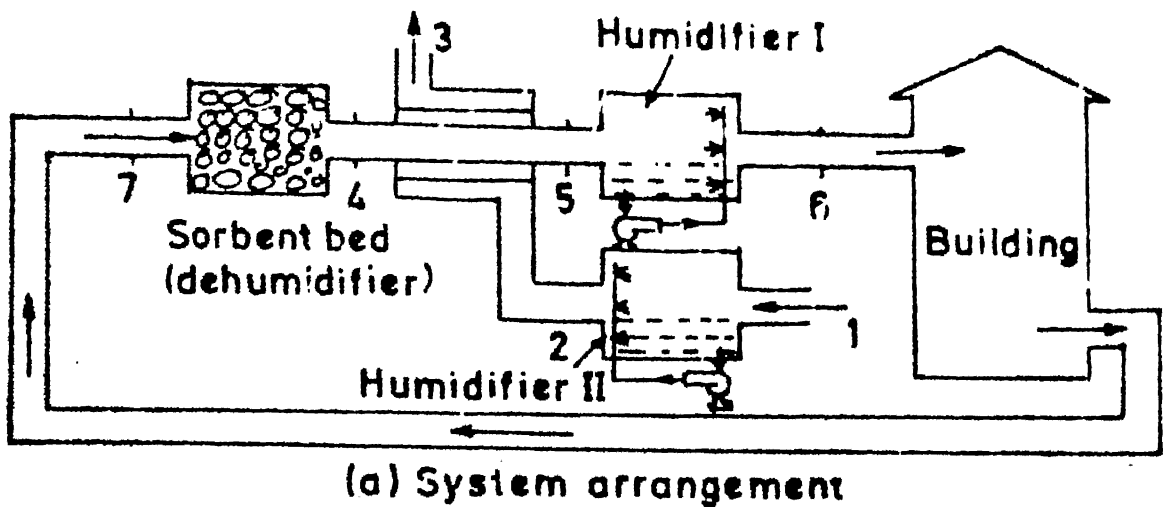


(a) System arrangement



(b) The processes on psychrometric chart

FIG.2.5 SYSTEM IV.



(b) The processes on psychrometric chart

FIG.2.6 SYSTEM V.

Among the systems described above, the system-III has been chosen for further analysis, even though the system-IV was found to be slightly better based on the perfect cooling of the adsorbent bed which is an hypothetical case. The system-III (Fig. 2.4) has been analysed for different inlet air conditions and for varying heat exchanger effectiveness and humidifier efficiency. The results obtained, **have been** discussed later.

It is worthwhile to note that the best system chosen involves additional components resulting in high cost. This aspect is, however, not investigated in the present **work**.

CHAPTER-3

EXPERIMENTAL SET-UP AND PROCEDURE

3.1 SYSTEM DESCRIPTION

In order to study the actual performance of the adsorption system, a test-rig was fabricated and installed. It comprises a sampling section in the inlet portion of the duct to get simulated condition of air by heating and humidifying and a dehumidifying section containing the adsorption bed as exhibited in Fig. 3.1.

The sampling section of the duct assembly includes the heating arrangement for air and a spray humidifier. This arrangement helps in providing an air-sample of the desired humidity and temperature condition. The air-sample is passed through an adsorbent bed kept at the end of the duct for dehumidification. The dehumidified air, thus obtained, may be passed through a sensible cooling system or an evaporative cooling system or a combination of both to achieve efficient cooling even under hot and humid climates.

The sorbent material becomes ineffective after being used as a dehumidifying agent for few hour(s) and

needs regeneration. This has been achieved by ~~after~~ drying of the solid adsorbent/absorbent in a solar dryer, during the day time and by an electrically heated chamber during the periods of nonavailability of the solar energy.

3.2 EXPERIMENTAL SET-UP

The schematic diagram of the experimental set-up as shown in Fig. 3.1 consists of the following main components:

- (i) Duct,
- (ii) Fan,
- (iii) Heating and humidifying arrangements and
- (iv) Dehumidifying arrangement.

The regeneration systems are shown separately in Figs. 3.2 and 3.3. Photographs of the complete dehumidifying section are shown in Figs. 3.1(a) and (b). The same for regeneration chambers have also been shown in Figs. 3.4 and 3.5. A detailed description of the above components is given below:

3.2.1 Duct

A metallic duct was fabricated from 24 gauge G.I. sheet having the cross-section 300 x 300 mm. and the length 3.6 m. A small duct having circular section (450 mm. dia.) at one end and square-section (300 x 300 mm) at the other, was attached to the duct for mounting of the

fan. The spray water of the humidifier was collected in a trough at the bottom of the duct. The duct is divided into the heating and humidifying sections and a section containing the adsorption bed. The duct is covered with thermocole sheets of 25 mm. thickness to minimize heat losses.

3.2.2 Fan

An exhaust fan was mounted at the inlet-end of the duct. It has the following specifications:

Make	: G.E.C.
Speed	: 900 RPM
Sweep	: 450 mm.
Voltage	: 220/240 volts A.C.
Power	: 145 watt.

The fan-speed was changed with the help of a variac to get air circulation at the desired flow rate.

3.2.3 Heating and Humidifying Arrangements

In the first part of the duct, three heaters were installed to heat the air. Each of the heaters consists of two 600 w electric coils, pressed between two 400 x 220 mm. aluminium sheets to provide larger surface area. They were kept in the vertical array through which the air was passed.

The next part of the duct contains a tank of the size 90 x 30 x 15 cm at its bottom. Six spray nozzles

spaced uniformly, were provided inside the duct to humidify the hot air. Water from the tank was forced through the nozzles by means of a pump. The rate of spray was governed by a globe-valve. A 3 KW heater was immersed in the tank to achieve the desired water temperature. The electrical energy input was controlled with the help of a variac.

3.2.4 Dehumidifying Arrangement

The following two arrangements were made for dehumidifying the hot and moist air using silicagel and copper sulphate:

- (a) Three wooden trays each of 25 cm width and 90 cm length were kept in the duct in horizontal position. The sorbent materials were spread uniformly in these trays and air was allowed to pass over the surface of the sorbent material.
- (b) A circular aluminium cylinder of diameter 15 cm and length 35 cm was used. A cooling coil of copper tube of 6 mm dia. was fitted inside the cylinder to cool the adsorbent bed. It was mounted at the centre of the duct. The open space of the duct around the cylinder was closed to allow the air to pass through the sorbent bed only.

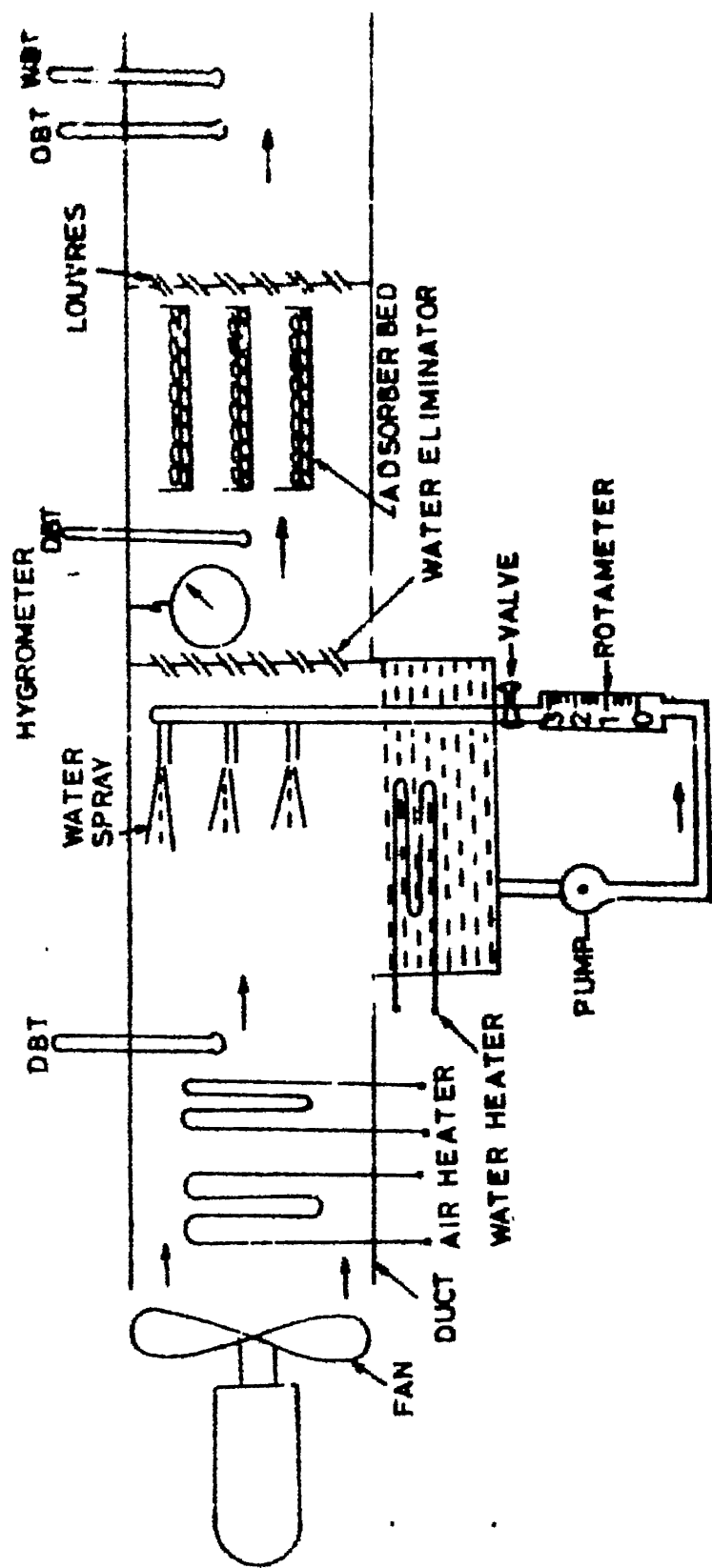
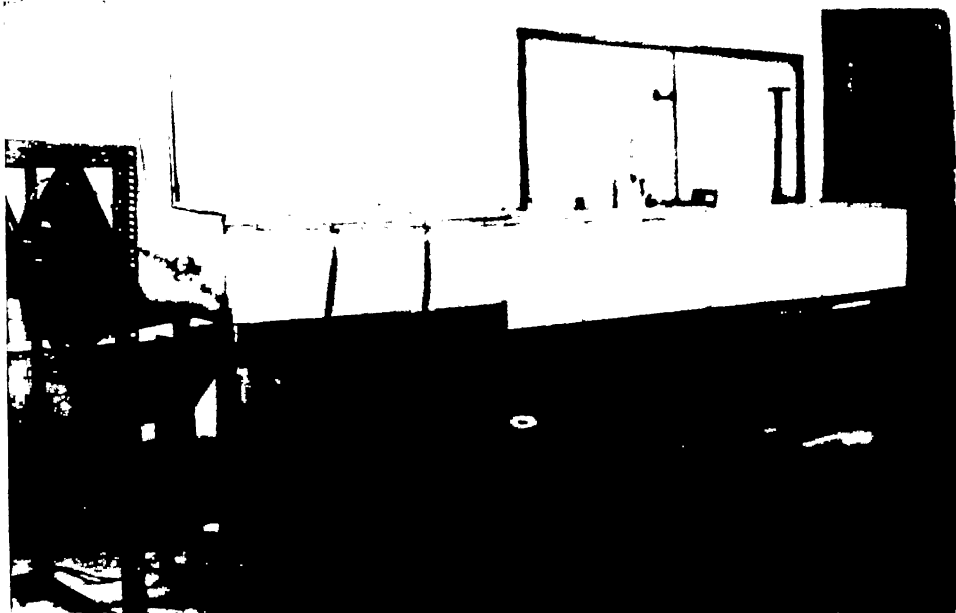
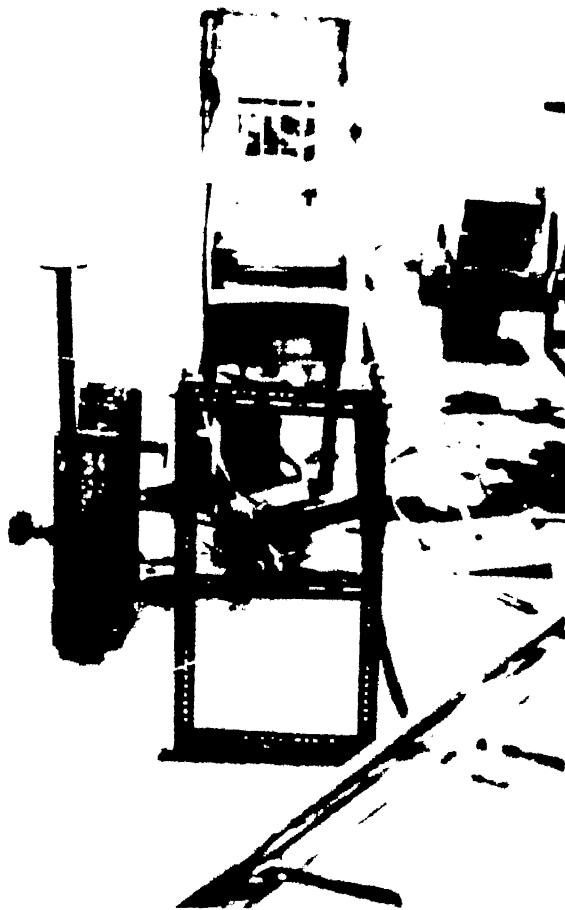


FIG.3-1 SCHEMATIC DIAGRAM OF DEHUMIDIFYING SECTION.



3.1(a) Complete View of Dehumidifying Section



3.1(b) Internal Details of Dehumidifying Section

3.2.5 Regeneration Chamber for Sorbents

Two types of regeneration chambers were used to reactivate the used silicagel and copper sulphate ;

- (i) a solar drier, where the solar radiation was utilized to regenerate the sorbent material and
- (ii) a chamber through which electrically heated air was passed. It was mainly used under circumstances when sun energy was not available. The heater capacity was 5 kW. The air was circulated by means of a blower having the following specifications:

Make : Wolf
Capacity : $1.46 \text{ m}^3/\text{min}$
Amps : 1.56
Voltage : 220/250 volts.

3.3 INSTRUMENTATION AND MEASUREMENTS

3.3.1 Temperature and Humidity Measurement

Temperatures at various sections were measured by mercury thermometers. The relative humidity was obtained using an induction type psychrometer. It consists of two thermometers to indicate dry and wet-bulb temperatures. They help determine the relative humidity of air by dint of the psychrometric slide rule. Hygrometer was also used to measure the relative humidity in order to have a double check.

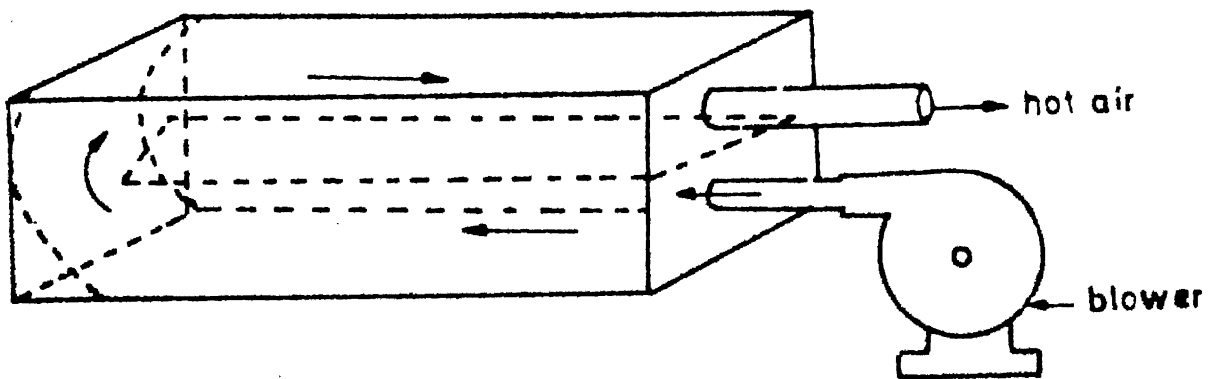


Fig. 3.2 Regeneration chamber using electrical energy.

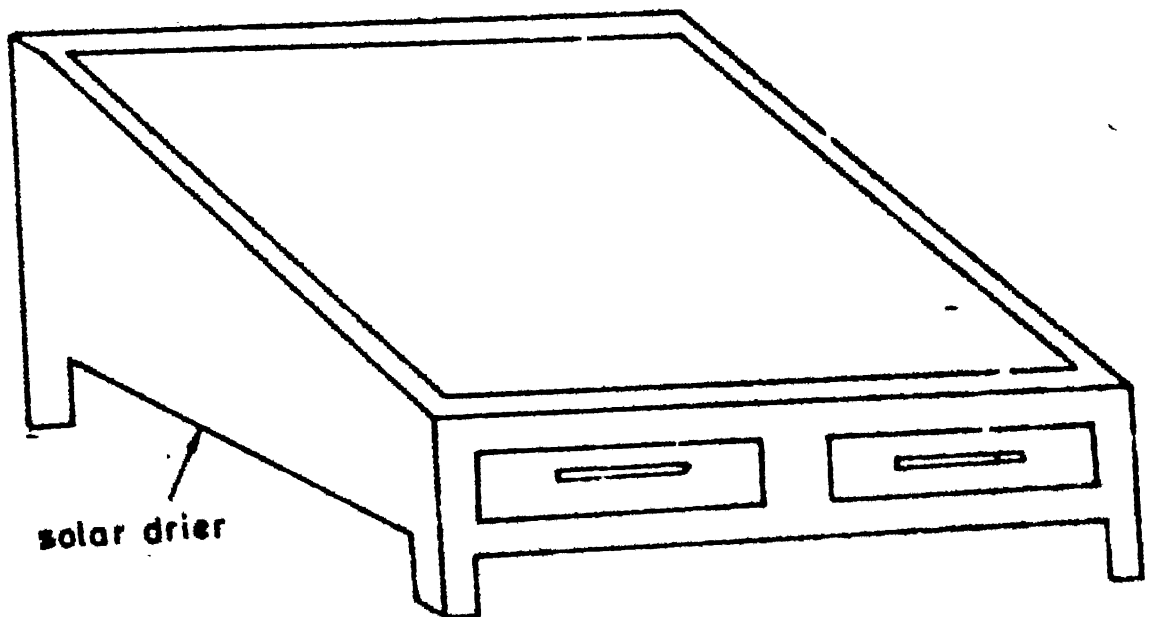
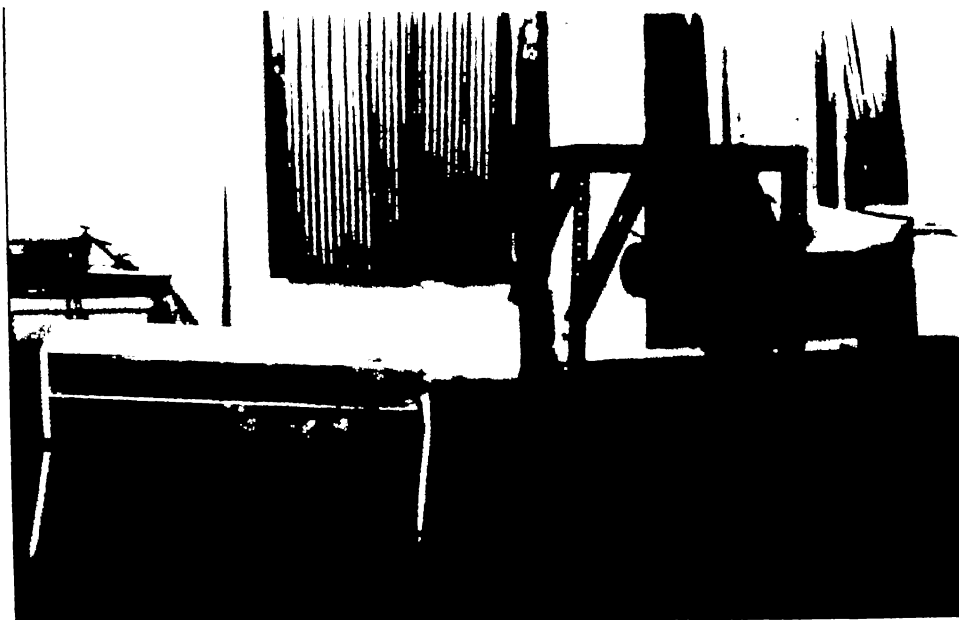


Fig. 3.3 Regeneration chamber using solar energy.



3.4 Complete View of Electrical
Regeneration Chamber



3.5 Solar Drier with Silicagel
and Copper Sulphate

3.3.2 Air-flow Measurement

The velocity of air was measured by means of a calibrated vane-type anemometer. The flow rate was then calculated by multiplying the area of cross-section of the duct and the air velocity. Specifications of anemometer were:

4" Biram Anemometer
8 Blade-Vane-Low Speed.

3.3.3 Water-flow Measurement

A calibrated rotameter was used to get the water flow-rate. The desired flow rates through spray nozzles and through cooling coils were regulated by control valves. Specifications of rotameter were:

Make : Brooks Instrument Co.
Type : 8-111C - 10
Range : 0 - 5 gpm.

3.4 TEST PROCEDURE

The heaters were first switched on about half an hour before the experiment was actually started to ensure constant inlet air condition. Also, the tank at the bottom of the duct was filled with water and the pump started to spray water through nozzles. At the start of the experiment, the inlet state of the air was noted down by means of a psychrometer. The temperature of the air was checked at the end of

heating chamber after every 30 minutes and the temperature as well as the relative humidity of the air were recorded, simultaneously, at the end of the humidifying chamber. The air was then dehumidified by silicagel as well as by copper sulphate kept in trays. However, it was observed that a significant quantity of air could not come in contact with the sorbent bed and hence, the dehumidification was incomplete. This difficulty was overcome by using a cylindrical container for the sorbent materials. The depth of the bed was kept about 15 cm in each case. The silicagel of mesh-size 6-10 was used. The condition of the dehumidified air was recorded, by a psychrometer after every five-minutes. Just in the beginning readings were taken at an interval of about 1 minute. The air velocity was kept fixed (60 m/min) through out the experiment for different sets of inlet conditions.

The above experiments were performed both under adiabatic and cooled conditions of the sorbent bed to compare the performance of the two systems. Silicagel was chosen as an adsorbent and the copper sulphate as an absorbent material. About one kg. of the material was used at a time. The process of dehumidification continued for about one and ^ahalf hours. The material was then shifted for regeneration either to a solar drier or to the electrically heated chamber.

It was found that the sorbent material was regenerated in about one and half hours time in the solar drier ~~only~~. It was then ready to be used again for dehumidifying the moist air. The sorbent material kept in the drying chamber was weighed after every 30 minutes and its temperature was also recorded simultaneously. This was done in order to determine the rate of regeneration.

Different inlet conditions were maintained by varying the inlet air and spray water temperatures. The experiment was repeated for different inlet air conditions.

The dehumidified air was passed through a sensible cooling system (a finned water cooled heat exchanger) having cylindrical silicagel bed and cooling coil. This was done to check the efficiency of the entire process.

Calcium chloride is much cheaper than the silica-gel and copper sulphate, but it changes into liquid on absorption of moisture from sample air. When it was kept in ^{an} electrically heated chamber maintained at 130 to 135°C for regeneration, it was found that it still acted as a dehumidifying agent.

CHAPTER-4

RESULTS AND DISCUSSIONS

4.1 ANALYSIS OF EXPERIMENTAL RESULTS

The experimental results have been carried out for silicagel and copper sulphate desiccants kept in trays and cylindrical container. The cooling coils have been provided in the latter in order to study the augmentation in its adsorbing capacity. Inlet conditions have been simulated corresponding to those of the coastal areas and rainy season. Some of the interesting results have been presented in the graphical form as detailed below.

4.1.1 Dehumidification in Adiabatic Beds

Figures 4.1 (a) and (b) exhibit the variations in exit T_{db} , T_{wb} and w with time for silicagel beds (tray type and cylindrical body). Evidently the humidity ratio increases gradually from its initial value of 0.0135 to 0.022 in about half an hour (Fig. 4.1(a)) and from 0.0075 to 0.022 in about fifteen minutes (Fig. 4.1(b)). Thereafter, it increases linearly with time. The rapid adsorption of moisture in the initial stages causes sharp rise in T_{db} , and then it starts decreasing. This is due to the fact

that the silicagel having high initial adsorption capacity liberates more heat of adsorption. As the adsorption capacity of the bed decreases, the heat of adsorption gets reduced resulting in reducing trend in T_{db} .

The wet-bulb temperature, to start with, increases due to replacement of entrapped dehumidified air in the bed at room temperature by the sampling air. And within a few minutes it assumes a constant value, about a few degrees Celsius higher than the wet-bulb temperature of the sampling air. This higher value seems to be due to release of the heat of adsorption, being greater than the heat of condensation.

The magnitudewise differences between values of T_{db} , T_{wb} and w for the two systems mentioned above may be interpreted as follows. In the cylindrical arrangement all the air comes in contact with the adsorbent granules. Therefore, the dehumidification rate is quite high, as also the heat of adsorption. In case of trays, only a part of the air seems to come in contact with the bed and mixes with the rest part ~~slightly inside~~ before leaving the trays. Hence the adsorption rate is less, rendering lower values.

The nature of T_{wb} and w for the copper sulphate absorbent bed is the same as that of the silicagel bed, but

magnitudewise they are less than that of the latter, Fig. 4.2. However, the nature of T_{db} in the beginning portion differs considerably from that of the silicagel bed. The lesser heat of absorption of copper sulphate seems to be the reason for the same.

The lower initial values of T_{db} and T_{wb} than the inlet temperatures and the initial sharp changes in about 5 minutes in the experimental results seems to be due to:

- (a) the initial bed temperature being slightly lower than the sampling air temperature,
- (b) the lower humidity of the air entrapped in the adsorbent bed and
- (c) the lower temperature ^{of the} granules of the bed acting as a sink for the incoming air.

4.1.2 Dehumidification by Cooled Beds

Water at room temperature has been used for cooling the bed enhancing its adsorption capacity, Fig. 4.3. It shows the time-wise variation in the exit dehumidified air conditions. The cylindrical shape is selected in view of maintenance of uniform flow through the bed and the better placement of coils in it. Yet, the cooling has not been done perfectly, the advantages are apparent due to larger moisture removal and reduced T_{wb} . Because, the lower is

the temperature of the adsorber bed, the higher is its capacity of moisture removal. The reduction in T_{wb} may be easily understood by plotting points on the psychrometric chart. It is, thus, seen that the bed should have been cooled by the air used for regenerative heat exchanger.

The nature of exit T_{db} and T_{wb} depends on the moisture content in air having other parameters and situations identical. The comparison between Figs. 4.3(a) and (b) reveals that T_{db} for the air with the larger moisture content shows an increasing trend in the beginning and then ^adecreasing nature for the same flow rate of cooling water through the bed. Evidently, the large adsorption of moisture from the sample air, having larger moisture content, releases higher heat of adsorption than that of air with lesser moisture content. This information would help in designing the capacity of heat exchanger for the bed.

For copper sulphate, the effect of cooling is not very advantageous as for the silicagel bed, Fig. 4.4, because the absorption capacity does not get ^asignificant enhancement. In addition, T_{wb} shows ^{an} increasing behaviour with time and is quite similar to the one found for silica-gel bed dehumidifying air with low moisture content. Also with the lapse of time as the adsorption capacity of the

bed decreases, T_{wb_e} of the leaving air tends towards the sample air wet-bulb temperature.

4.1.3 Comparative Performance of Silicagel and Copper Sulphate Beds

Figure 4.5 shows the time-wise variation in moisture contents in the adiabatic silicagel and the cooled copper sulphate bed . Despite the difference between the inlet states for both the materials, a reasonable comparison is possible. In case of the cooled copper sulphate bed the more humid inlet condition is more favourable from the dehumidification point of view. Yet, it is seen that the moisture content (i.e. adsorbed moisture from air) is more in the case of silicagel at each time.

A plot of dehumidification rate (i.e., $\frac{dx}{dt}$) vs. moisture content (i.e., x) is exhibited in Fig. 4.6. It is seen that the dehumidification rate of silicagel, even in the unfavourable condition, is much more than that of copper sulphate (absorbing moisture in the more favourable condition). Therefore, it is expected that the cooled silicagel bed will be far superior to the cooled copper sulphate bed under identical operations.

4.1.4 Desorption by Solar Drier

The foregoing experimental results reveal that the adiabatic and cooled beds become almost ineffective

after about two hours depending upon the quantity of the sorbent material and the moisture content of air. Therefore, either fresh sorbents or reactivated used sorbents may be applied at the above intervals. Since, sorbents are quite costly materials, they cannot be thrown away. Hence, the latter method is the most common practice eliminating the storage of large amount of sorbents for continuous operation of the system.

In view of the utilization of solar energy, the used sorbents (silicagel and copper sulphate) are dried simultaneously in the flat plate solar drier (having variable temperature, Figs. 4.7 and 8). It has been found that the reactivation period is about one and ^ahalf hours. The reactivation time will be further reduced if the same is carried out at noon or in the afternoon time. However, for the same x value (upto $x = 0.17 \text{ kg}_w / \text{kg}_A$) the copper sulphate shows higher regeneration rate. As soon as x value exceeds 0.17 (as is generally found), the regeneration rate of silicagel becomes higher than the copper sulphate, Fig. 4.9. From this aspect the copper sulphate has dehumidification and desorption characteristics opposite to each other. Overall results, thus, envisage the feasible choice for the silicagel adsorbent bed for air conditioning or other cooling purposes, where temperature requirement is not too low.

4.1.5 Real Psychrometric Processes

The process 1-2 represents the sensible heating (for the set-up shown in Fig. 3.1) taking place in the duct, Fig. 4.10. Thereafter, the spray of hot water yields the sample air at state-3. This high moisture and ^{high} temperature air is passed through the silicagel adsorbent bed having cooling coils where moisture has been reduced to state-4 after 10 minutes time. The sensible cooling of this air by a finned water cooled heat exchanger produces air at state-5. After state-5 the results are found theoretically. The cooling by outgoing air from the room after humidification, produces the dehumidified air at state-6. The humidification of this air enables the achievement of state-7. This condition is quite close to the comfort condition for human beings of tropical countries.

4.2 BEHAVIOUR OF SORBENTS DURING DEHUMIDIFICATION AND REGENERATION PROCESSES

About 2 to 3 times of regeneration of copper sulphate after absorption of moisture brings about changes from its crystalline shape ^{to} powdered form. It provides excessive flow resistance due to blocking of voids during the course of operation. To the contrary, silicagel retains its shape for many cycles. Its replacement by a fresh charge after a long period (around 4 to 5 years) as

compared to regular replacement of copper sulphate is the most promising ^{aspect} for dehumidification. Therefore, copper sulphate, though cheaper (Rs. 12/kg), will be extremely expensive in comparison to silicagel (Rs. 20/kg).

The sorption and desorption processes of silicagel can easily be detected due to distinct colour changes. The same is not so sharp in the case of copper sulphate. This behaviour of the former would enable a user to select the sorption/desorption sequence at an appropriate time.

Calcium chloride bed is not suitable for dehumidification of air as it becomes liquid during dehumidification process and cannot be regenerated even by a good flat plate collector giving 120°C of the operating temperature [18]. When electrically heated air at around 130 to 135°C was passed through the calcium chloride bed, it became liquid. ~~Subsequent to this, looking at the regeneration~~. It indicates that the regeneration of this absorbent is expected to be possible only if concentrators (being much costlier than the flat plate collectors) are used.

4.3 SYSTEM ANALYSIS

The comparative performance of five systems (Chapter 2) shows that System-III (Fig. 2-4) is found to be the most suitable choice. For this system the effects of various parameters (heat exchanger effectivenesses

$(\varepsilon_1, \varepsilon_2)$, humidifier efficiencies (η_{H1}, η_{H2}) have been studied for a typical environmental condition, Fig. 4.11. The effect of efficiency of humidifier I on the inlet room air condition is much more pronounced than that of humidifier II. Similarly, the effectiveness (ε_2) of regenerative heat exchanger II has significant effect on the achievement of lower room inlet air condition. Therefore, it requires better attention on the choice and maintenance of the performance ^{of} humidifier I and regenerative heat exchanger II. The effects of other parameters $(\varepsilon_1, \eta_{H1})$ is much less pronounced than the above parameters.

For the given values of parameters, the effect of inlet environmental conditions on the achievement of inlet air condition ^{to} room is exhibited in Fig. 4.12. It shows that the final air condition is not greatly affected.

Though the system-III is seen to be a viable alternative to the conventional air conditioning systems for comfort condition, a further improvement is possible by cooling of the adsorbent bed with the help of air streams passing through the heat exchangers I and II.

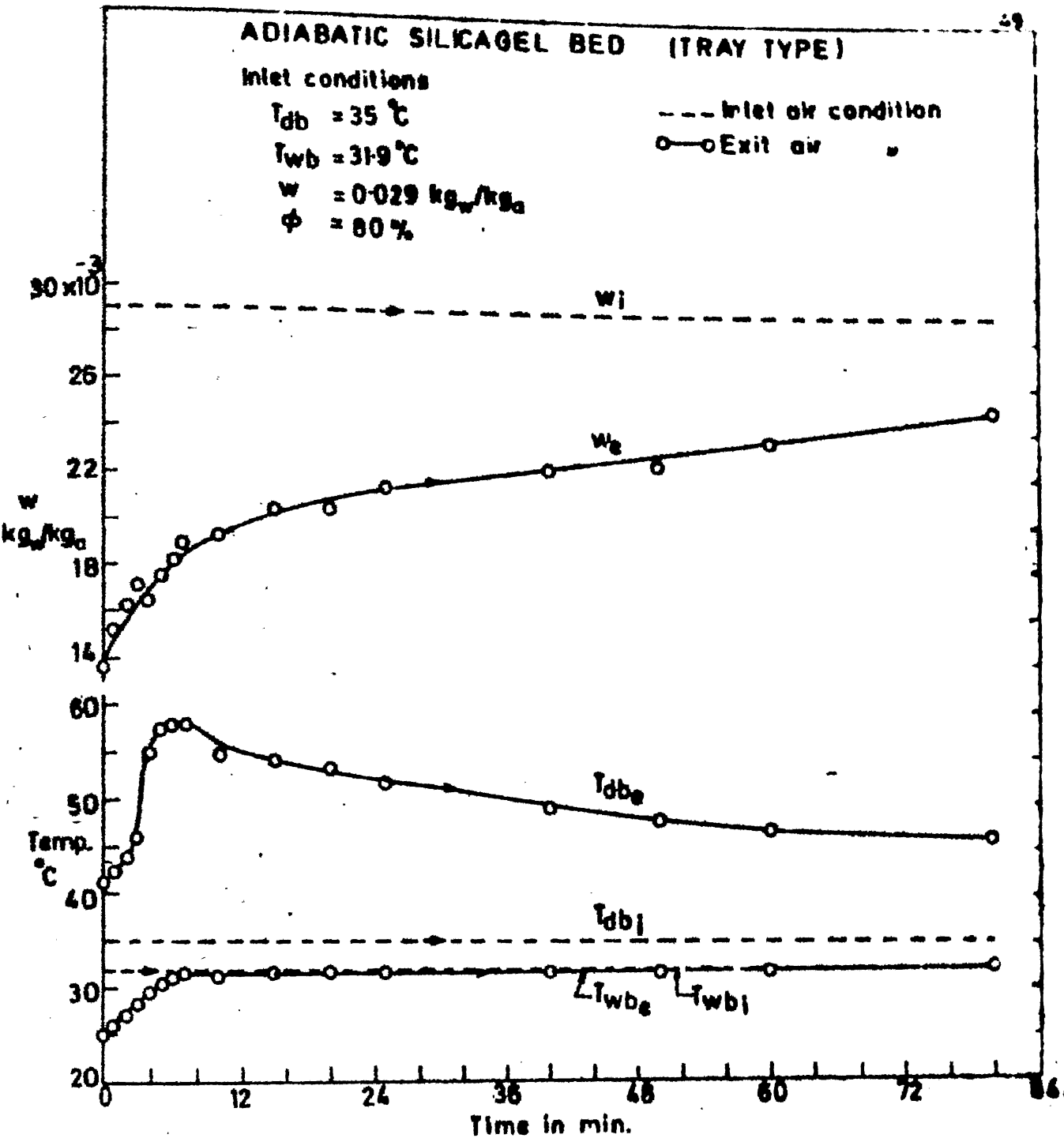


FIG.4.1(a) TIME-WISE VARIATION IN T_{dbe} , T_{wb_e} , w_e OF DEHUMIDIFIED AIR.

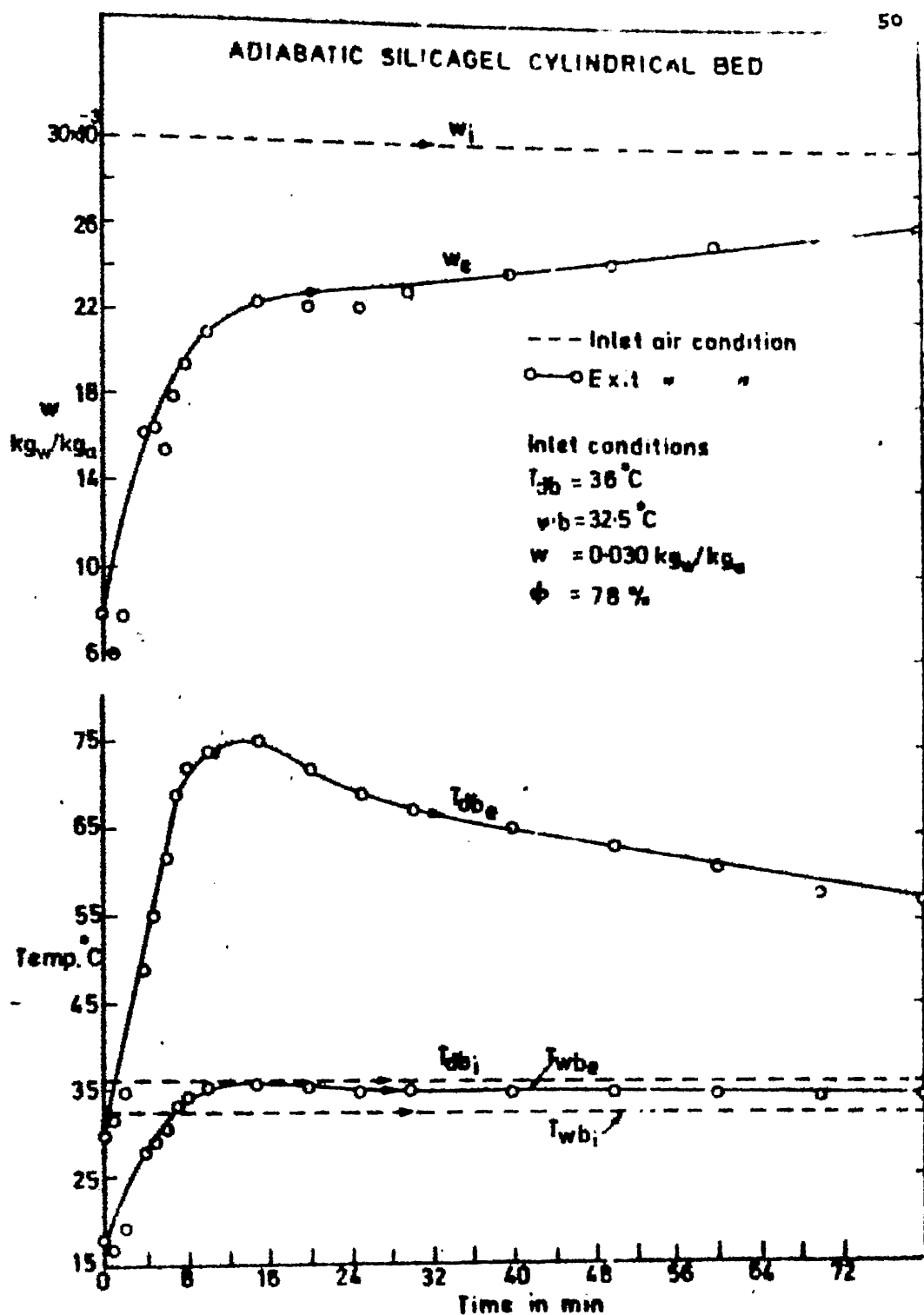


Fig.41(b) TIME-WISE VARIATION IN T_{db_e} , T_{wb_e} , w_e OF DEHUMIDIFIED AIR.

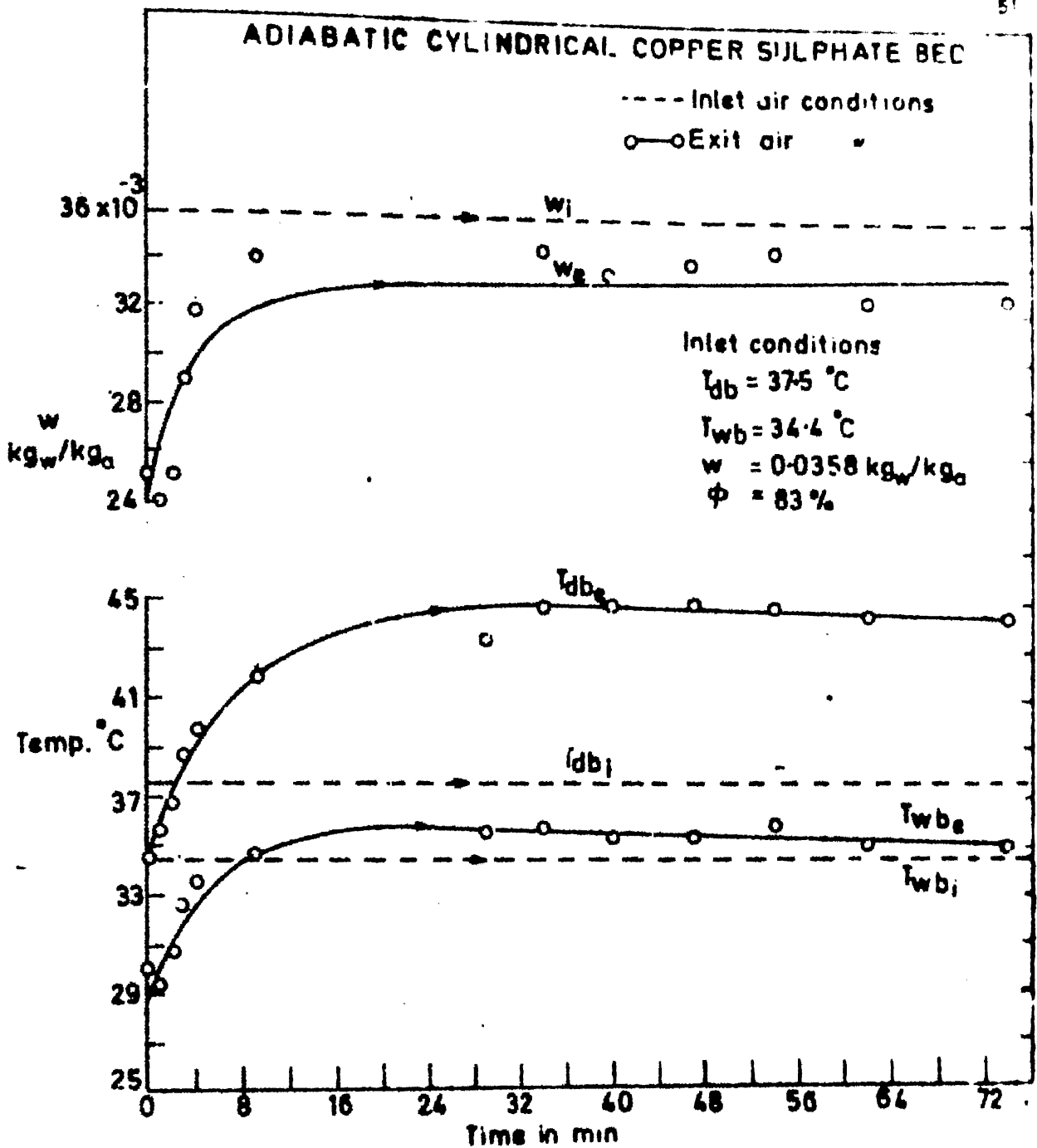


FIG. 42 TIME-WISE VARIATION IN t_{db_e} , t_{wb_e} , w_e OF DEHUMIDIFIED AIR.

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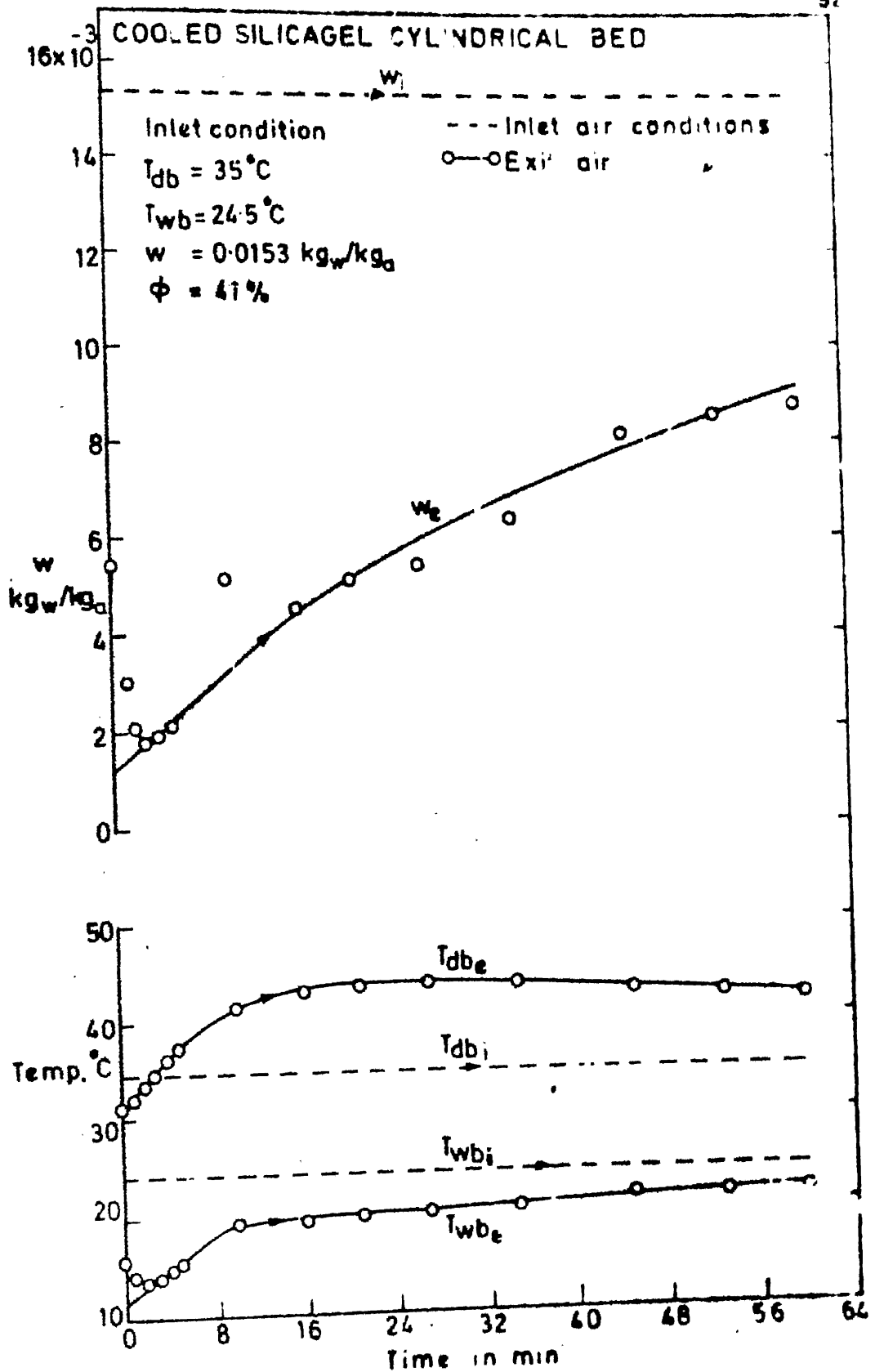


FIG. 4.3(a) TIME-WISE VARIATION IN T_{db_e} , T_{wb_e} , w_e OF DEHUMIDIFIED AIR.

COOLED SILICAGEL CYLINDRICAL BED

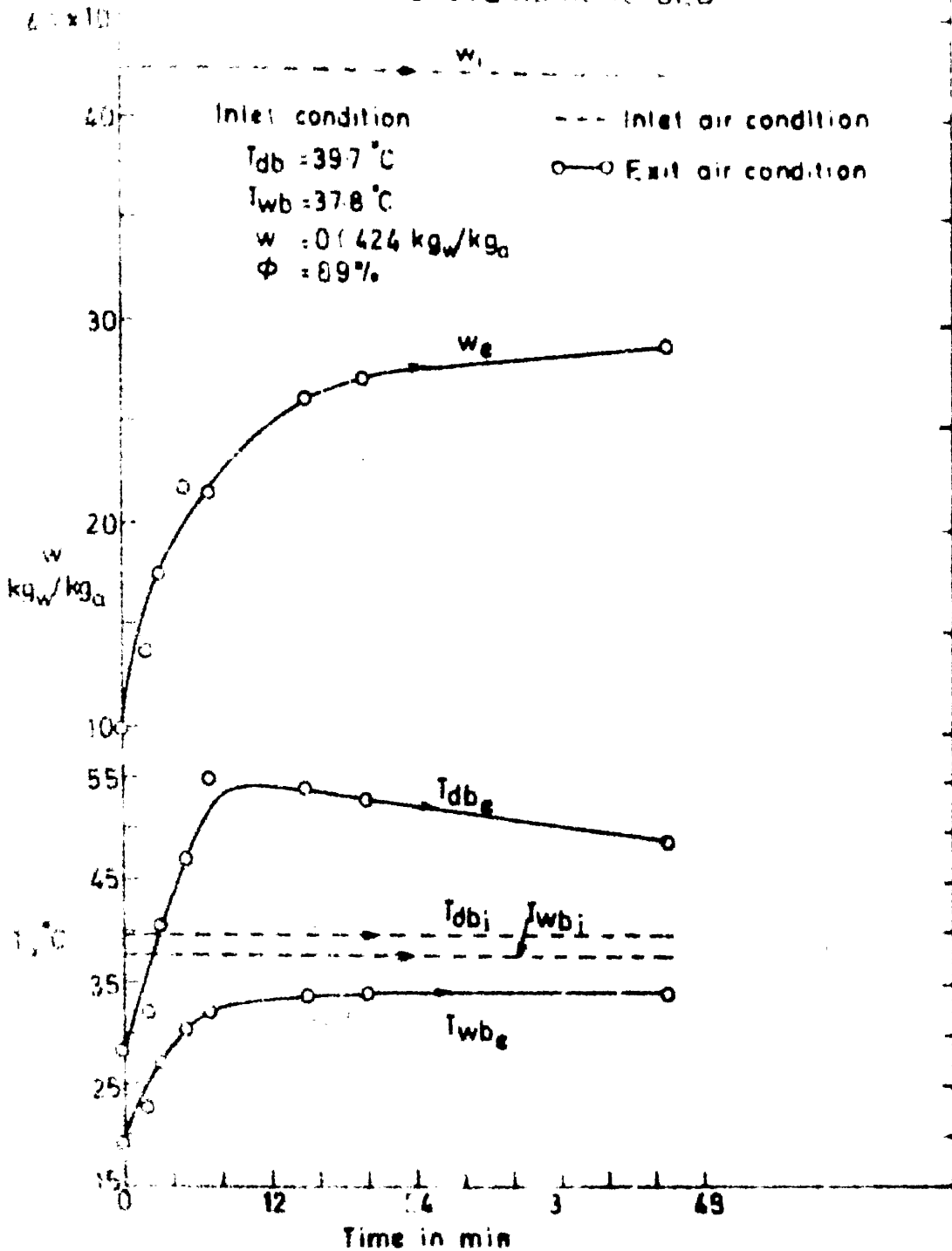


Fig 43(b) TIME-WISE VARIATION IN T_{db_e} , T_{wb_e} , w_e OF DEHUMIDIFIED AIR.

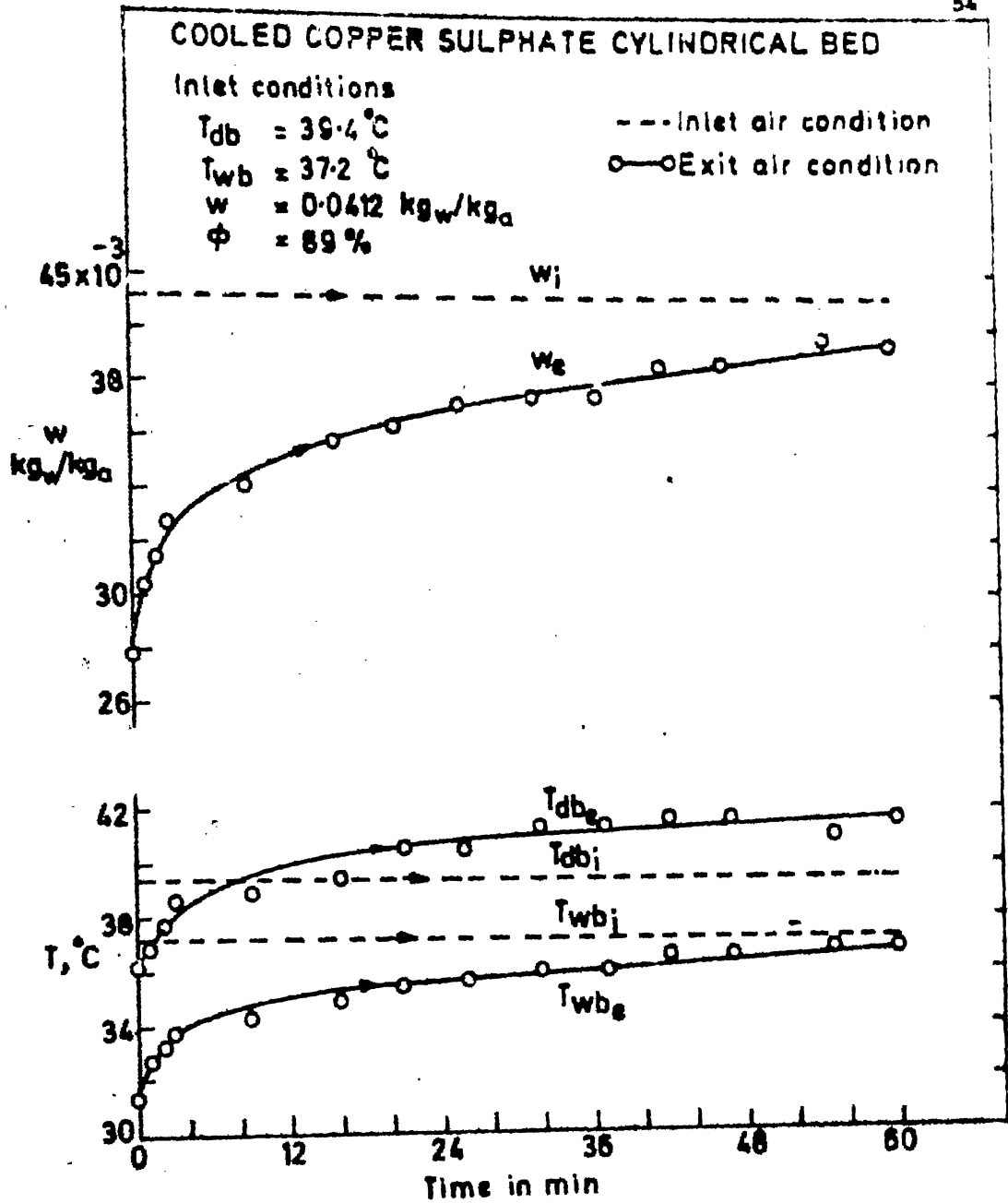


FIG.4.4 TIME-WISE VARIATION IN T_{db_e} , T_{wb_e} , w_e OF DEHUMIDIFIED AIR.

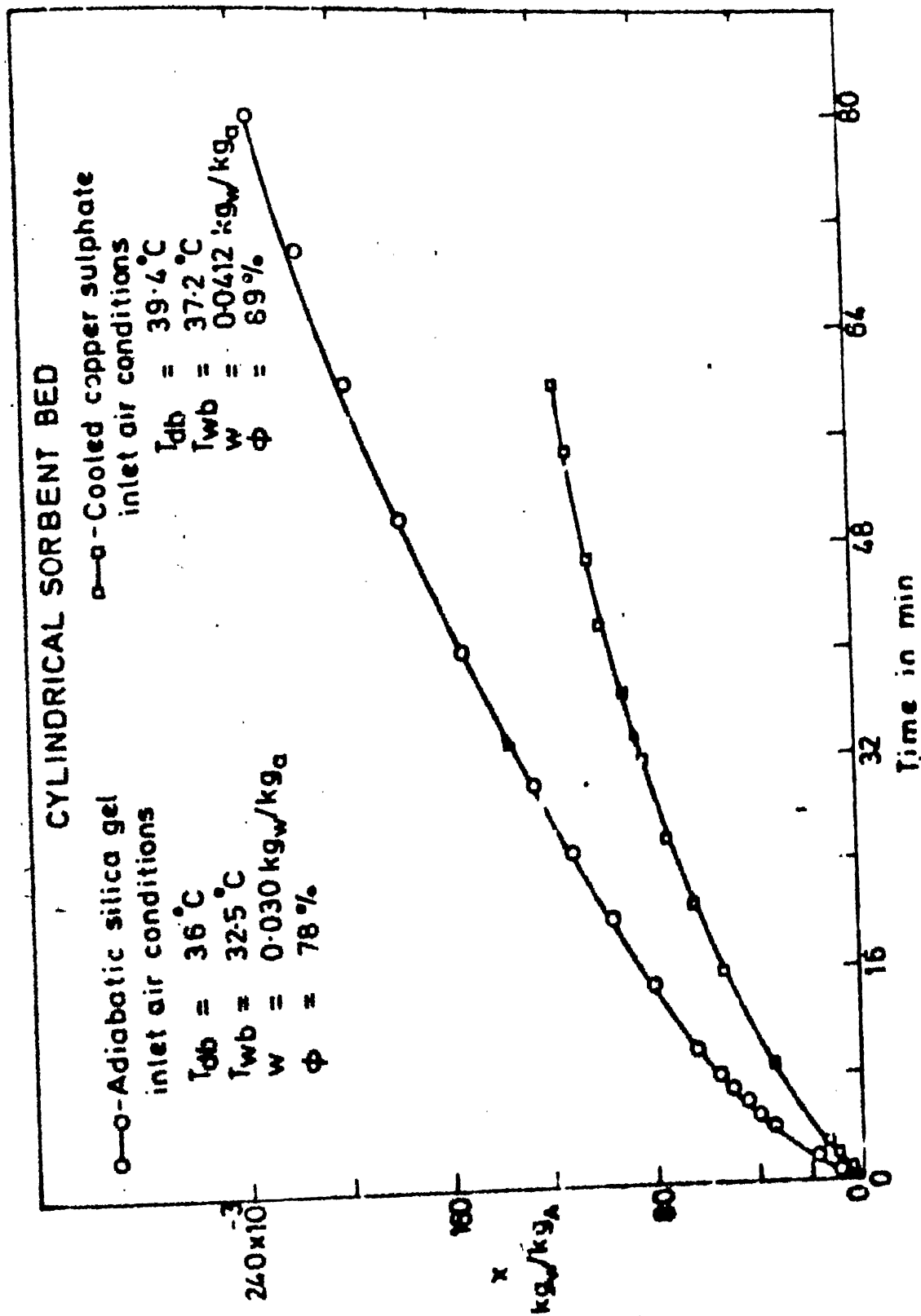


FIG.4.5 TIME-WISE VARIATION IN MOISTURE CONTENT (x) OF SORBENT BED.

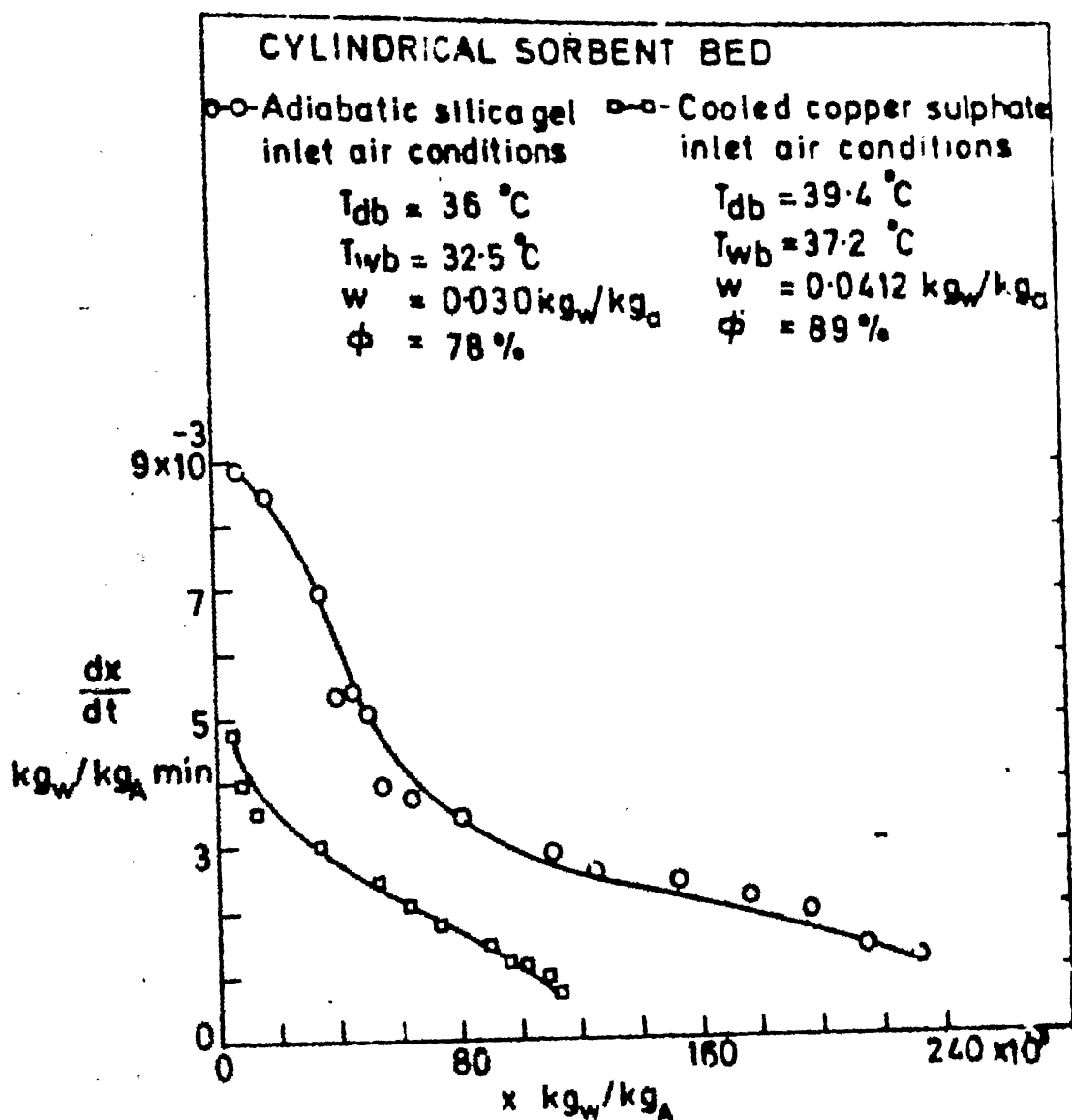


FIG. 4.6 VARIATION IN DEHUMIDIFICATION RATE (dx/dt) WITH BED MOISTURE CONTENT (x).

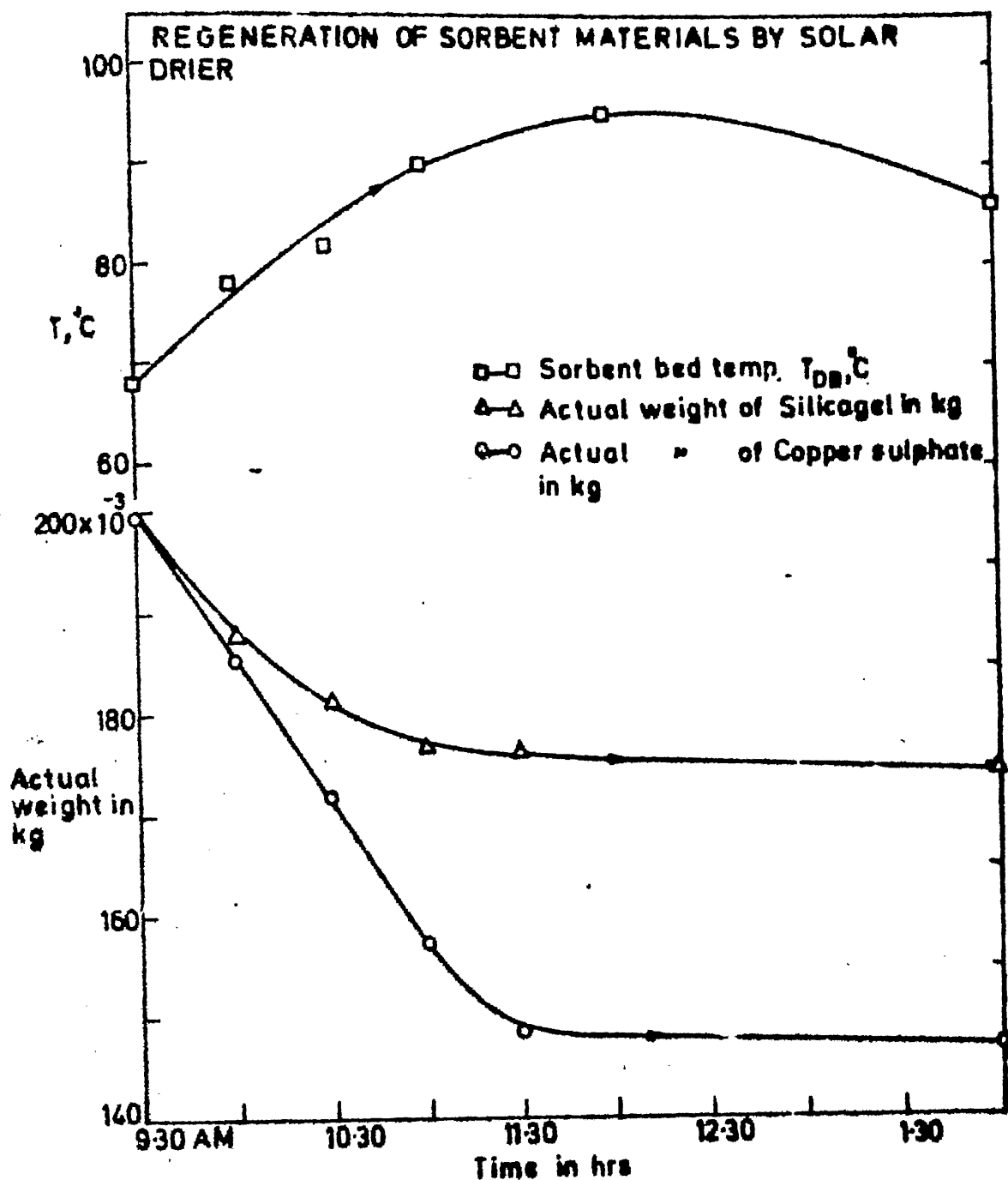


FIG.47 TIME-WISE VARIATION IN BED TEMPERATURE AND ACTUAL WEIGHT OF SORBENT MATERIALS.

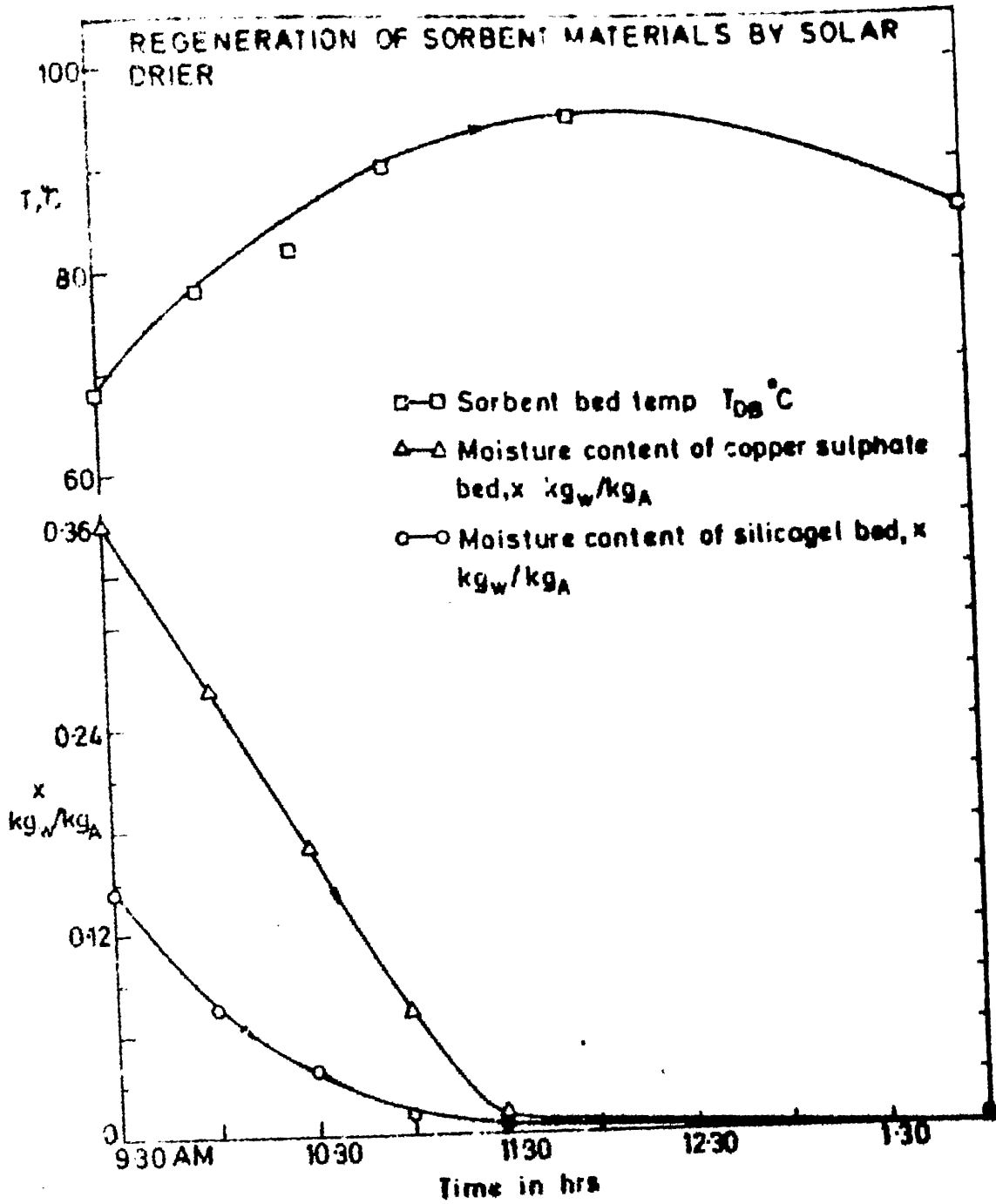


FIG.4.8 TIME-WISE VARIATION IN MOISTURE CONTENT (x) OF SORBENT MATERIALS.

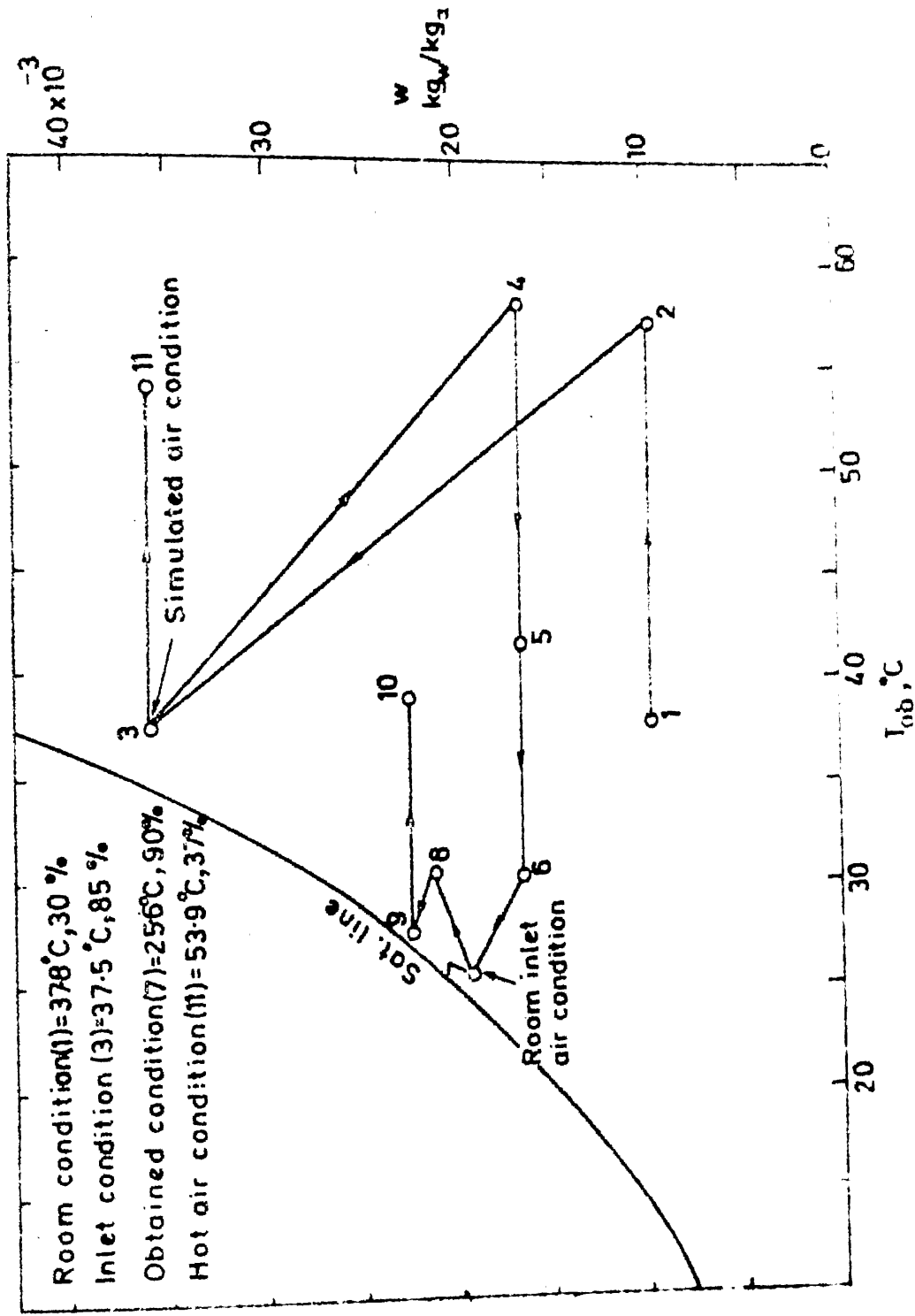


FIG. 4.10 STATE POINTS SHOWN ON PSYCHROMETRIC CHART
 (For system III)

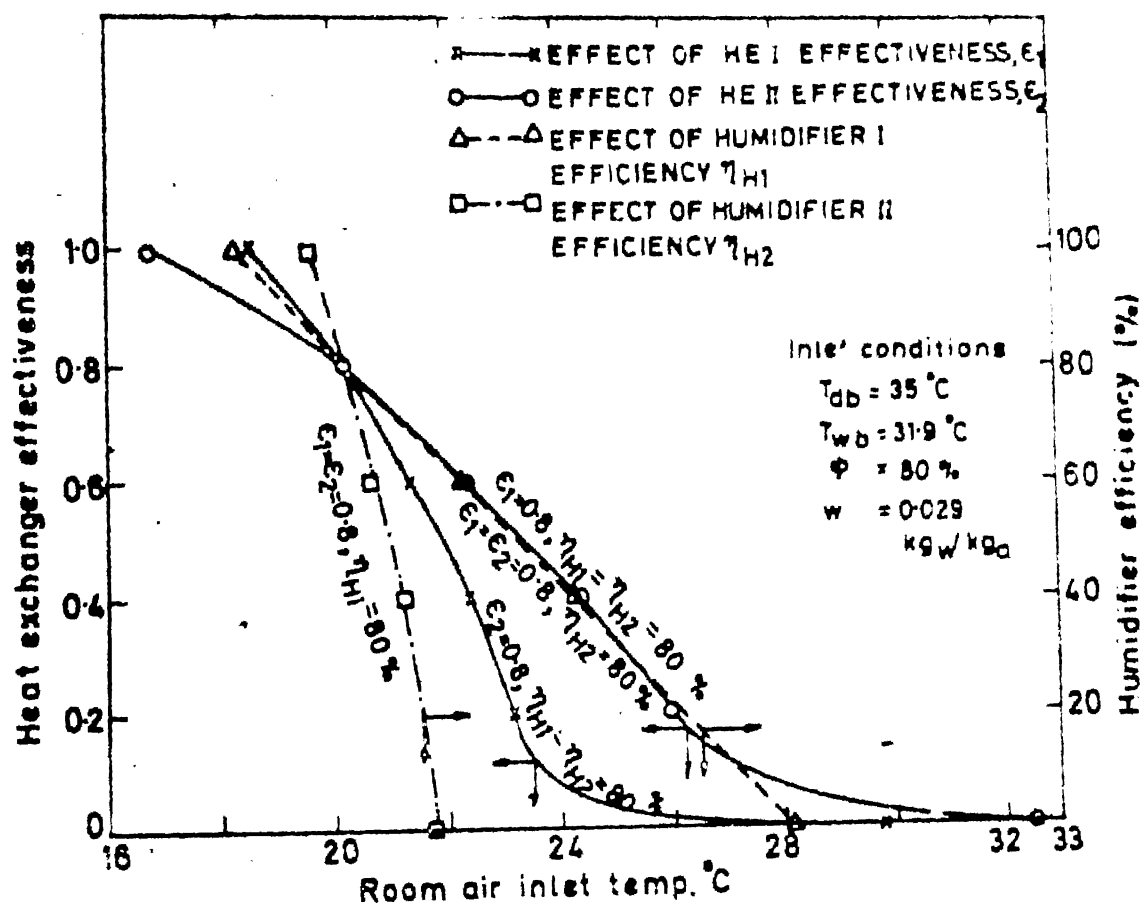


FIG.4.11 EFFECT OF HEAT EXCHANGER EFFECTIVENESS AND HUMIDIFIER EFFICIENCY ON FINAL TEMP. FOR SYSTEM III.

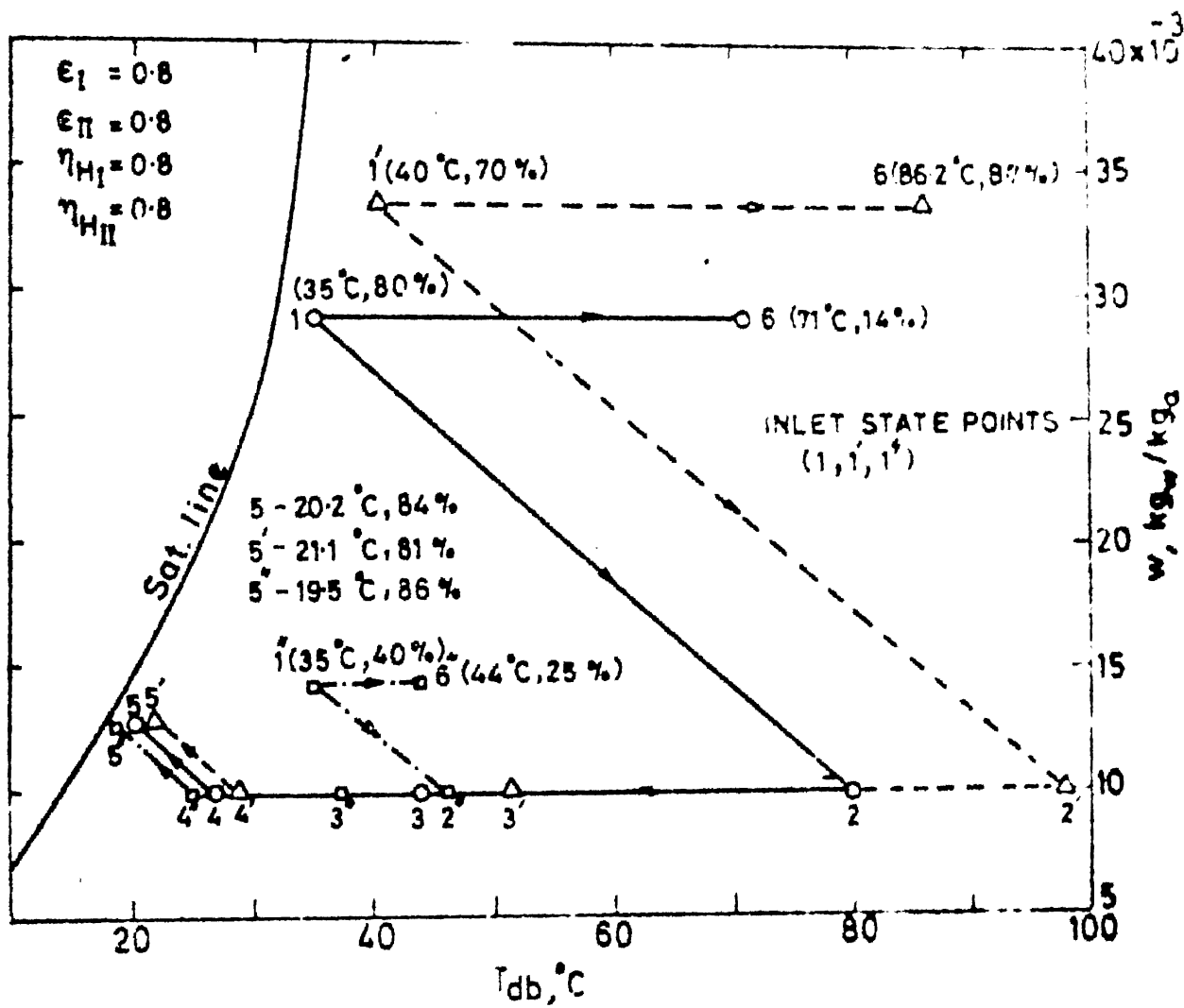


FIG.4.12 EFFECT OF INLET CONDITIONS ON FINAL TEMPERATURE FOR SYSTEM III.

CHAPTER-5

CONCLUSIONS AND SUGGESTIONS

5.1 CONCLUSIONS

From the present experimental results and system analysis the following conclusions have been put forth:

1. The silicagel bed has much better performance than that of copper sulphate bed under identical conditions. It implies, therefore, that the lesser amount of the former will be involved for the same capacity of the system.
2. The rate of regeneration of silicagel supersedes to the regeneration rate of copper sulphate bed for large value of $x(> 0.17)$ generally met in practice. The same order of dehumidification period and regeneration period based on flat plate solar drier makes it possible for the cyclic operation.
3. Copper sulphate does not retain its crystalline shape after 2 to 3 cycles. It becomes powder causing blocking of voids and thereby renders excessive flow resistance. To the contrary, the silicagel retains its shape for many-many cycles.

Its replacement by a fresh charge after a long period makes it possible to operate the system much more economically as compared to copper sulphate.

4. The sorption and desorption of silicagel can easily be detected due to distinct colour changes. The same is not sharp in case of copper sulphate. This behaviour of the former would be quite helpful in changing the processes.
5. The rate of water adsorption of silicagel is much higher than that of the copper sulphate, and it remains uniform for a long period. This characteristic of the former is more beneficial for the actual performance of a system.
6. The cooling of the bed brings about a quite significant augmentation in adsorption capacity of adsorbent (silicagel) bed. It implies, therefore, that the cooling of the bed by cooling air seems to be a better choice than cooling of the dehumidified air. However, for copper sulphate the same rate of cooling by external source does not yield much improvement.
7. Out of the study of five systems employing sorbents for dehumidification of air followed by its

cooling and humidification, system-III (Fig. 2-6) is found to be the most suitable choice. However, effectiveness of the regenerative heat exchanger-II and efficiency of humidifier-I have pronounced effect on the achievement of final condition of air entering the room.

Overall, the system-III using silicagel bed seems to be a viable alternative to conventional air conditioning system for comfort condition. It may, however, not be possible to maintain comfort condition exactly like conventional systems. Still the choice falls on the present system due to the decreased system cost, less electrical bill, low temperature shocks during entering and leaving the conditioned space.

5.2 SUGGESTIONS FOR THE FUTURE WORK

In the time bound M. Tech. programme, it was not possible to go in ^{to} the depth of the investigation in view of involvement of large number of variables and considerable time in the fabrication and commissioning of the set-up. Therefore, following suggestions are put forth as a scope for future investigation.

1. The experiments may be conducted to cover wider ranges of variables to provide generalized results.

2. The economics of the whole system should also be considered and results be compared in view of increasing cost of energy.
3. The study of ^{the} complete system should be undertaken to get actual performance of the system.
4. For further improvement of the system, the air coming out of the heat exchanger-I can be used for regeneration purpose. Therefore, the heat of adsorption can be used as a part of regeneration heat.

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APPENDIX-A

SAMPLE CALCULATION FOR SYSTEM-III

Detailed step-wise calculations for the system-III are given for finding out the final states for the following inlet (1) conditions:

$$T_{db} = 35^{\circ}\text{C} \quad , \quad T_{wb} = 31.9^{\circ}\text{C}, \quad w = 0.029 \text{ kg}_w/\text{kg}_a,$$

$$\phi = 80\%$$

- Assumptions:
- (i) Dehumidification process is adiabatic
 - (ii) Dehumidified air humidity ratio,
 $w_2 = 0.010 \text{ kg}_w/\text{kg}_a$
 - (iii) Heat exchanger effectiveness,
 $\epsilon_1 = \epsilon_2 = 0.8$
 - (iv) Humidifier efficiency, $\eta_{H1} = \eta_{H2} = 80\%$
 - (v) Heat capacities of the hot and the cold air are equal, i.e., $m_h c_{p_h} = m_c c_{p_c}$
 - (vi) Rise in air DBT in the building = 5°C
 - (vii) Rise in air humidity ratio in the building = $0.002 \text{ kg}_w/\text{kg}_a$.

From the psychrometric chart the state-2 has been found out along constant wet-bulb (i.e., 31.9°C) line and at a moisture level of $0.010 \text{ kg}_w/\text{kg}_a$.

Therefore,

Dry and hot air-state-2

$$T_{db} = 80^{\circ}\text{C}, \quad T_{wb} = 31.9^{\circ}\text{C}, \quad w = 0.010 \text{ kg}_w/\text{kg}_a,$$

$$\phi = 3.4\%.$$

The state-3 has been calculated by using the formula for effectiveness of the heat exchanger.

$$\epsilon_I = \frac{T_2 - T_3}{T_2 - T_1}$$

$$\epsilon_I = 0.8, \quad T_2 = 80^{\circ}\text{C}, \quad T_1 = 35^{\circ}\text{C}$$

$$\therefore T_3 = 44^{\circ}\text{C}.$$

Moderately hot and dry air-state-3

$$T_{db} = 44^{\circ}\text{C}, \quad T_{wb} = 23.3^{\circ}\text{C}, \quad w = 0.010 \text{ kg}_w/\text{kg}_a$$

$$\phi = 17.5\%$$

Initially, the room is assumed to be at ambient condition, i.e., at $T_{db} = 35^{\circ}\text{C}$ and $T_{wb} = 31.9^{\circ}\text{C}$

$$\eta_{H_{II}} = \frac{T_6 - T_7}{T_6 - T_{wb}}$$

$$\text{Now } \eta_{H_{II}} = 0.8, \quad T_6 = 35^{\circ}\text{C}, \quad T_{wb} = 31.9^{\circ}\text{C}$$

$$\therefore T_7 = 32.6^{\circ}\text{C}.$$

Iteration-1

So, in the first iteration, the temperature T_4 will be calculated as follows:

$$\epsilon_{II} = \frac{T_3 - T_4}{T_3 - T_7}$$

or

$$0.8 = \frac{44 - T_4}{44 - 32.6}$$

$$T_4 = 34.9^\circ\text{C and } T_{wb} = 20.8^\circ\text{C}$$

Now temperature T_5 is calculated as follows:

$$\eta_{HI} = \frac{T_4 - T_5}{T_4 - T_{wb}}$$

or

$$0.8 = \frac{34.9 - T_5}{34.9 - 20.8} \text{ or}$$

$$T_5 = 23.6^\circ\text{C, } w_5 = 0.0142 \text{ kg}_w/\text{kg}_a$$

Temperature and humidity gain in the building.

$$T_6 = T_5 + 5 = 23.6 + 5 = 28.6^\circ\text{C}$$

$$w_6 = w_5 + 0.002 = 0.0162 \text{ kg}_w/\text{kg}_a ; \quad T_{wb} = 22.8^\circ\text{C}$$

Temperature T_7 is calculated as follows:

$$\eta_{HII} = \frac{T_6 - T_7}{T_6 - T_{wb}} \quad \text{or} \quad 0.8 = \frac{28.6 - T_7}{28.6 - 22.8}$$

or $T_7 = 23.9^\circ\text{C}$

Iteration-2

Now, in the 2nd. iteration, temperature T_4 will be

$$\epsilon_{II} = \frac{T_3 - T_4}{T_3 - T_7} \quad \text{or} \quad 0.8 = \frac{44 - T_4}{44 - 23.9}$$

or $T_4 = 27.9^\circ\text{C, } T_{wb} = 19.1^\circ\text{C (from psychrometric chart)}$

$$\eta_{H_I} = \frac{T_4 - T_5}{T_4 - T_{wb}}$$

$$0.8 = \frac{27.9 - T_5}{27.9 - 19.1} \quad \text{or} \quad T_5 = 20.9^\circ\text{C},$$

$$w = 0.013 \text{ kg}_w/\text{kg}_a \text{ (from psychrometric chart)}$$

After gain in temperature and humidity, the condition will be

$$T_6 = T_5 + 5 = 20.9 + 5 = 25.9^\circ\text{C}$$

$$w_6 = w_5 + 0.002 = 0.013 + 0.002 = 0.015 \text{ kg}_w/\text{kg}_a$$

$$T_{wb} = 21.9 \text{ (from psychrometric chart)}$$

$$\eta_{H_{II}} = \frac{T_6 - T_7}{T_6 - T_{wb}}$$

$$0.8 = \frac{25.9 - T_7}{25.9 - 21.9} \quad \text{or} \quad T_7 = 22.7^\circ\text{C}$$

Iteration-3

After the 3rd iteration, condition at 4 will be

$$\epsilon_{II} = \frac{T_3 - T_4}{T_3 - T_7}$$

$$0.8 = \frac{44 - T_4}{44 - 22.7} \quad \text{or} \quad T_4 = 27.0^\circ\text{C}, \quad T_{wb} = 18.7^\circ\text{C}$$

$$\eta_{H_I} = \frac{T_4 - T_5}{T_4 - T_{wb}}$$

$$0.8 = \frac{27 - T_5}{27 - 18.7} \quad \text{or} \quad T_5 = 20.4^\circ\text{C},$$

$$w_5 = 0.0128 \text{ kg}_w/\text{kg}_a \text{ (from psychrometric chart)}$$

Calculation:

Condition after gain in temperature and humidity ratio will be

$$T_6 = 20.4 + 5 = 25.4^\circ\text{C}$$

$$w_6 = 0.0128 + 0.002 = 0.0148 \text{ kg}_w/\text{kg}_a$$

$$T_{wb} = 21.7^\circ\text{C}$$

$$\eta_{H_{II}} = \frac{T_6 - T_7}{T_6 - T_{wb}}$$

$$0.8 = \frac{25.4 - T_7}{25.4 - 21.7} \quad \text{or} \quad T_7 = 22.4^\circ\text{C}$$

Iteration-4

After 4th iteration, the condition will be

$$\epsilon_{II} = \frac{T_3 - T_4}{T_3 - T_7}$$

$$0.8 = \frac{44 - T_4}{44 - 22.4} \quad \text{or} \quad T_4 = 26.7^\circ\text{C}, \quad T_{wb} = 18.6^\circ\text{C}$$

$$\eta_{H_I} = \frac{T_4 - T_5}{T_4 - T_{wb}}$$

$$0.8 = \frac{26.7 - T_5}{26.7 - 18.6} \quad \text{or} \quad T_5 = 20.2^\circ\text{C},$$

$$w_5 = 0.0127 \text{ kg}_w/\text{kg}_a$$

Condition after gain in temperature and humidity ratio

$$T_6 = T_5 + 5 = 25.2^\circ\text{C},$$

$$w_6 = w_5 + 0.002 = 0.0147 \text{ kg}_w/\text{kg}_a$$

$$T_{wb} = 21.7^\circ\text{C}$$

$$\eta_{H_{II}} = \frac{T_6 - T_7}{T_6 - T_{wb}}$$

$$0.8 = \frac{25.2 - T_7}{25.2 - 21.7} \quad \text{or} \quad T_7 = 22.4^\circ\text{C}$$

Here, we see that the value of T_7 is the same as its previous value obtained in iteration-3. So further iteration is not required. Now final conditions at every state points are given below:

State-4 $T_{db} = 26.7^\circ\text{C}$, $T_{wb} = 18.6^\circ\text{C}$, $\phi = 44\%$,
 $w = 0.010 \text{ kg}_w/\text{kg}_a$

State-5 $T_{db} = 20.2^\circ\text{C}$, $T_{wb} = 18.6^\circ\text{C}$, $\phi = 84\%$,
 $w = 0.0127 \text{ kg}_w/\text{kg}_a$

State-6 $T_{db} = 25.2^\circ\text{C}$, $T_{wb} = 21.7^\circ\text{C}$, $\phi = 72\%$,
 $w = 0.0147 \text{ kg}_w/\text{kg}_a$

State-7 $T_{db} = 22.4^\circ\text{C}$, $T_{wb} = 21.7^\circ\text{C}$, $\phi = 91\%$,
 $w = 0.016 \text{ kg}_w/\text{kg}_a$

The final conditions of state points 1, 2 and 3 are given previously. Condition at point 9 and 8 can be calculated as follows:

Assuming no heat loss to the surrounding, temperature T_9 is given as

$$(T_9 - T_1) = (T_2 - T_3) \quad \text{or} \quad T_9 = T_1 + (T_2 - T_3)$$

$$\text{or} \quad T_9 = 35 + (80 - 44) \quad \text{or} \quad T_9 = 71^\circ\text{C}$$

∴ State-9 $T_{db} = 71^{\circ}\text{C}$, $T_{wb} = 37.8^{\circ}\text{C}$, $\phi = 14\%$,
 $w = 0.029 \text{ kg}_w/\text{kg}_a$ (from psychrometric chart)

Similarly the equation for temperature T_8 is given as follows:

$$(T_8 - T_7) = (T_3 - T_4) \quad \text{or} \quad T_8 = T_7 + (T_3 - T_4)$$

$$\text{or} \quad T_8 = 22.4 + (44 - 26.7) \quad \text{or} \quad T_8 = 39.7^{\circ}\text{C}$$

∴ State-8 $T_{db} = 39.7^{\circ}\text{C}$, $T_{wb} = 25.9^{\circ}\text{C}$, $\phi = 34\%$,
 $w = 0.016 \text{ kg}_w/\text{kg}_a$.

Thus, the final condition at each point calculated by iterative method, is presented below:

TABLE A-1

State Points	$T_{db}, ^{\circ}\text{C}$	$T_{wb}, ^{\circ}\text{C}$	$\text{kg}_w^w/\text{kg}_a$	$\phi \%$
State-1	35	31.9	0.029	80
State-2	80	31.9	0.010	3.4
State-3	44	23.3	0.010	17.5
State-8	39.7	25.9	0.016	34
State-9	71	37.8	0.029	14

TABLE A-2

No. of Iterations	State-4							State-5			
	T _{db} °C		T _{wb} °C		kg _w /kg _a		φ %	T _{db} °C		T _{wb} °C	
	T _{db} °C		T _{wb} °C		kg _w /kg _a		φ %	T _{db} °C		T _{wb} °C	
1	34.9	20.8	0.010	26.5	23.6	20.7	0.0142	76			
2	27.9	19.1	0.0103	43	20.9	19	0.013	83			
3	27.0	18.7	0.0102	44	20.4	18.7	0.0128	84			
4	26.7	18.6	0.0102	46	20.2	18.6	0.0127	84			

	State-6							State-7			
	T _{db} °C		T _{wb} °C		kg _w /kg _a		φ %	T _{db} °C		T _{wb} °C	
	T _{db} °C		T _{wb} °C		kg _w /kg _a		φ %	T _{db} °C		T _{wb} °C	
1	28.6	22.8	0.0162	65	23.9	22.8	0.0172	92			
2	25.9	21.9	0.015	70	22.7	21.9	0.0161	92			
3	25.4	21.7	0.0148	71	22.4	21.7	0.016	93			
4	25.2	21.7	0.0147	71	22.4	21.7	0.016	93			